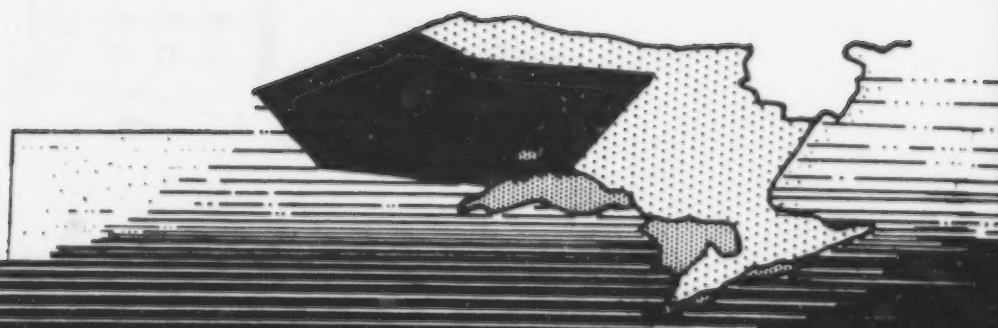




Ontario

Ministry of
Natural
Resources

**NORTHWESTERN ONTARIO FOREST
TECHNOLOGY DEVELOPMENT UNIT**

NWOFTDU Technical Report #30. 159 pp. 1990

A CROP-PLANNING PROCESS FOR
NORTHERN ONTARIO FORESTS

by

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This project was partially funded by the Canada-Ontario Forest Resource Development Agreement.

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FOREWORD

Crop planning as outlined in this report can be an important step in building a solid linkage between forest management and timber supply in Ontario. The process provides the volume forecasts that are missing from the standard area-regulation approach, and the process provides an analytical tool to design silviculture regimes that have the right kind of power in the unique context of each forest. Used as an analytical tool, crop planning will maximize the learning of each manager about the forest being managed. The result should be forest management that is designed to more efficiently achieve specific goals in specific forests.

G.L. Baskerville, 1990
Dean, Faculty of Forestry
University of New Brunswick

EXECUTIVE SUMMARY

The Challenge of Forest Management

A major challenge to every forest manager is to manipulate the structure and development of a particular forest so it will meet the current and future demands placed on it. Adaptive forest management entails planning a future course for a forest, implementing the plan, monitoring implementation progress and forest development, and replanning to accommodate new understanding and perhaps new goals for the forest. Preparing an implementable management plan for a forest is a complex decision-making process that must determine which action sets will best satisfy demands for benefit flows from the forest. For most types of forest benefits, especially timber, this decision-making process may be called crop planning. In a nutshell, crop planning matches forest-management objectives with levels of harvest and silviculture required to meet the stated objectives.

The Situation in Ontario

In the Ontario context, we can consider a forest to be synonymous with the administrative concept of the forest management unit. Thus, a forest is a rather large collection of stands of various types, ages and site qualities. In forest management, the forest is the level at which objectives are set, and these provide the context for all harvest and silviculture decisions that the manager must make. Indeed, good forest management is strongly determined by the degree to which the manager knows what the effects of stand-level silvicultural actions are on attainment of forest-level objectives. For example, managers ought to be aware that plantations established at 3.0 m spacing will contribute



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management, to be used to increase foresters' understanding of the possibilities and requirements in coaxing desired benefit flows out of the forests they manage.

A Crop Planning Process for Northern Ontario Forests

The crop planning process has three basic phases: a) an exploratory phase where forest production possibilities are analyzed and initial forest objectives set; b) a silvicultural strategy phase which uses tools of economic analysis to determine the most cost-efficient way to meet performance targets for certain forest types; and c) a final forest analysis phase in which the most efficient harvest and silvicultural schedules are chosen to meet the forest-level objectives. These three phases are briefly described below in terms of timber supply, although the principles of crop planning are equally applicable in management of wildlife habitat, recreation, biodiversity, and a host of other forest benefits.

In the initial exploratory analysis, forest-level dynamics are simulated using a volume-based forest simulator. Key elements in preparing for the simulation analyses are grouping the forest's stands into so-called forest classes, and developing "yield curves" (predictions of stand development over long periods of time) to represent patterns of change in each forest class. The yield curves comprise the vital bridge between forest-level planning and stand-level implementation of silviculture. Unfortunately, solid data for construction of yield curves for Ontario forests are scarce. Therefore, foresters need to apply knowledge of their specific forests, combined with basic concepts of growth and yield, in constructing first-approximation yield curves for use in crop planning. The uncertainties in such curves can be progressively

reduced as foresters monitor their forests and re-analyze stand responses to silvicultural interventions.

In the second phase of crop planning, the most cost-efficient silvicultural "ground rules" are developed that, when implemented, should make stands grow along the yield curves selected in the forest analysis. A key variable in determining cost efficiency of silviculture is plantation spacing. The traditional economic indicators of present net worth and benefit-cost ratio are used in relative terms to rank alternative plantation spacings and silvicultural options.

The main result of the second phase "forest-class analysis" is a recommended set of silvicultural ground rules, the associated yield curves of which may be slightly different than those used in the initial forest analysis. Thus, a final forest analysis is necessary for checking how well forest objectives are met using the new yield curves. In addition, the forest-level costs of the silvicultural strategies are compared with the value of the additional wood supply obtained by implementing the strategies (i.e., calculating the costs and benefits associated with the so called allowable cut effect).

To complete the cycle of adaptive management, crop planning is followed by field application of the silvicultural strategies or ground rules, and the monitoring of actual treatment responses to get feedback to improve the next round of crop planning. In this feedback, the manager evaluates the degree to which the silvicultural strategies achieved the results predicted in crop planning.

Implementing Crop Planning

The Ministry of Natural Resources already has a functioning administrative framework, i.e., the Timber Management Planning Process, within which crop planning as described here can be implemented. The current process of timber management planning already requires a substantial amount of forest analysis, including updating and analysis of inventory data and calculations for area regulation of the forest. The benefits of implementing volume-based crop planning within this framework are numerous and powerful:

- a) Volume-based crop planning provides an alternative way to achieve a balanced forest, a particularly meaningful approach since mills are consumers of even flows of timber volumes that are rather difficult to achieve with strict area regulation.
- b) Crop planning forces strong attention to justification of silvicultural programs in the context of their contribution to helping meet forest-level objectives.
- c) Crop planning forces strong attention to explicit forecasting of forest resource possibilities, which in turn forces explicit statements of assumptions about forest-stand behaviour over time. Explicit assumptions can be tested through directed research, while implicit assumptions must remain untested forever, which is not particularly appealing if they turn out to be wrong!
- d) Crop planning helps managers discover a range of production possibilities for a forest, each with an associated silvicultural program and costs. Thus, for example, current objectives for a forest may be seen to be unachievable with current and planned silviculture, or alternatively, current objectives may be seen to be achievable with much less than current and planned silviculture. Perhaps much more ambitious objectives can be achieved with a carefully targeted silvicultural program. Such possibilities are impossible to discover without a simulation-based crop planning analysis.

There are no technical barriers to implementation of crop planning for Crown forests in Ontario. Technically, all that is required is a basic micro-computer, a forest resource inventory in digital form, a forest-inventory simulator (e.g., "FORMAN"), and a forest manager with a good understanding of forest growth. The manager needs to understand the process, and needs the

technical knowhow to implement the analyses and, most important to interpret them.

Lessons from Some Crop Planning Examples

In preparing the crop planning process described here, we have undertaken analyses for some simplified yet realistic sample forests (i.e. spruce working group of a Thunder Bay District Forest). Our results are described in detail in the main report, mainly to demonstrate how the process works and what kinds of messages the analyses can yield. Here are some examples of these messages:

- a) the crop plan for a forest will be unique to that forest because of its unique structure, unique objectives, and unique harvest and silviculture strategies required;
- b) plantation spacing regime or density is a key variable in determining cost-efficiency of silvicultural ground rules;
- c) for forests where wood shortages are expected within a few decades, wide plantation spacing regimes and pre-commercial thinning seem warranted; and
- d) lowering the acceptable minimum average tree size for harvesting can significantly increase a forest's sustainable harvest volume.

Next Steps

The crop planning process presented here is a start and a challenge for better ideas and developments. It is meant primarily to assist foresters to develop local silvicultural ground rules that reflect the needs of specific forests. As noted, the process can easily be implemented within the framework of the Timber Management Planning Process.

The adoption and implementation of volume-based forest simulation that has already started in Northern Ontario will undoubtedly continue. We encourage this development, especially if it occurs through intelligent application of

crop planning. Our proposed process improves on current implementations of forest simulation in several ways:

- a) it further strengthens the links between forest-level planning and stand-level applications;
- b) it elevates plantation density or spacing regime as a major variable influencing forest development, harvest possibilities and silvicultural costs;
- c) it develops economic theory into useful indicators for evaluation purposes; and
- d) it challenges foresters to develop their own yield curves based on biological knowledge and available data.

Assistance to Northern Ontario foresters in applying crop planning is being developed along two lines. First, a software package that facilitates volume-based forest simulation and forest-class economic analysis is under preparation. Second, workshops are being planned to introduce the crop planning process to field foresters and give guidance in using the software and interpreting results of the analyses.

ACKNOWLEDGEMENTS

In the spring of 1988, G. Oldford, Director of Forest Management Branch, and E. Murphy, Director of Operations for Northern Ontario, asked me to address the age-old question for foresters: "What is the optimum planting density for Northern Ontario conifers?" In 1988, the normal intertree spacing was a constant 2 m spacing for all species, on all sites and for all product objectives.

In the first two drafts of this report, we concentrated on that question until it became apparent that our efforts were directed at a symptom (2 m spacing regime) and not at causes of the real problem which is lack of crop planning. To solve this problem, we had to build an approach that would encourage forest managers to develop unit-specific forest-management objectives and solve unit-specific forest-management problems.

I believe we have not answered the original question posed, but we have developed a usable process which will allow forest managers to answer this question for their own forests.

Many thanks to G. Baskerville, of the University of New Brunswick, who influenced and helped with the final drafts of this paper. I appreciate especially his contribution in converting the "crop planner" from a stand-alone model to an integrated forest-stand model. Special thanks to K. Caruk who typed this massive document and to L. Siczkarski who drafted the illustrations. Thanks, too, to the scientific and field personnel who provided "creative criticism" on the various drafts of this paper.

All of the above people contributed to the report, but the final analyses and interpretations are the responsibility of the authors.

A.J. Willcocks

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1.0 INTRODUCTION

The challenge for a forest manager is to produce goods and services ranging from timber to recreational opportunities from a particular forest in quantities and qualities sufficient to meet anticipated demand. With respect to timber, the decision-making process which determines the most appropriate management strategies can be termed "crop planning." Crop planning consists of determining the most suitable management options from a wide array of alternative courses of action so that the objectives for a forest, e.g. a timber-supply area, can be attained at the least cost. Forest-management objectives are a function of potential forest outputs (e.g., fibre yield, habitat) and the unique dynamics of the forest.

Foresters in Ontario tailor their management options to categories of stands which are described either in the Forest Resource Inventory (FRI) as "working groups" or in the Forest Ecosystem Classification (FEC) as "treatment units." In either case, the stand represents a population of trees on an area of any size and of relatively homogeneous site productivity where tree development follows a predictable pattern.

When considering stand-level management options, it is difficult to foresee their cumulative effect on forest dynamics and contribution to overall forest objectives. This is because each stand intervention has an impact on forest structure and therefore on the products that can be produced from the forest over time. Forecasting forest response to an array of stand interventions requires lengthy preparation of data followed by a tedious set of calculations. As a result, foresters in Ontario have tended to concentrate on stand-management decisions and stand-management decision models such as stand investment-analyses models or density-management diagrams (e.g., Drew and

Flewelling 1979) without due regard to the overall impact of these actions on the forest.

Reliance on stand-level models encourages questions such as "What is the most cost-efficient silvicultural treatment to regenerate this stand into high production conifers?", instead of, "How should this stand be treated, if at all, to meet forest-level objectives?". Indeed, Reed (1989) observed that there is a general absence of strategic planning at the forest level in Canada. He cited the concentration of funds in planting operations instead of forest tending or precommercial thinning as a prime indicator of this deficiency. He questioned whether the emphasis in British Columbia's recent Forest Resource Development Agreement on planting backlog NSR (not sufficiently restocked) areas will actually solve an apparent wood shortage beginning in the period 2015-2020. Similarly, more than 85,000 ha were regenerated in Northern Ontario in 1985-86 by artificial or natural means at a cost of over \$150 million. To what extent did this help solve forest- management problems or achieve forest objectives?

In An Audit of Management of the Crown Forests of Ontario (Baskerville 1986), questioned the level of crop planning on units he studied by stating:

The choice of amount of silviculture is apparently based on budget availability to carry it out. Specifically there was no evidence in the cases examined that the amount of silviculture for the unit had been determined with respect to some biological situation in the forest structure of the unit as it related to long term flow of raw materials. One would expect the amount of silviculture specified in a plan to be needed to maintain a desired level of wood flow, but as has been seen wood flow was only superficially examined in the plans, and as a result silviculture type, and amount, were not chosen on this basis. Under these circumstances, it is only possible to evaluate the effectiveness of silviculture in terms of whether it was sufficient in amount to meet the assigned target since the basis for it is unknown, and in any event was not related to an analysis of needs within a Unit ... Thus it is not possible to judge if the stand silviculture being applied is solving a forest management problem.

In short, many foresters are carrying out silvicultural activities at the stand level without considering the changes these actions will cause at the forest level, or whether overall needs from the forest will be better met because of the actions. In such cases, silviculture is an "article of faith". Working against effective crop planning are the following:

1. Foresters are, for the most part, trying to plan their crops using an intuitive or informal approach. In natural-resource management, this is usually ineffective because of the complex environment in which these decisions are made (Dykstra 1976).
2. No simple crop-planning process for undertaking consistent analyses has been developed and adopted by management foresters in Ontario. This more formalized approach, based on computerized mathematical models, will allow the analysis of many "what if" scenarios in a consistent manner.

Thus, the goal of this report is to introduce and demonstrate the potential of a practical crop-planning process which allows the forest manager to develop silvicultural and forest-management strategies responsive to forest objectives. The crop-planning process links the forest with its stands, resulting in more efficient achievement of forest-level objectives.

The crop-planning process illustrated is useable for forest-level decision making. As Baskerville (1989a) noted, it is intended to be a first step in linking forest objectives to stand-management applications. The process will no doubt evolve using principles of adaptive management in which feedback on process application will likely change the crop-planning process over time.

For any process to be used intelligently, there must be a clear understanding of its major components. For the crop planner this means a fundamental understanding of forest and stand dynamics (e.g., Baskerville 1979) and forest economics.

The report begins with an overview of the crop planning process and its major components. The remainder of the report illustrates the use of the process in some simple examples. These examples reveal that forest managers have a significant amount of flexibility in meeting forest objectives by varying the harvest schedules and silvicultural treatments. The assumptions underlying these case studies were made on the basis of generally available information and were intended to be reasonable approximations for a specific example forest. The text ends with a summary of major conclusions, a statement of follow-up work that would further develop the crop-planning process, and advice to forest managers on how to begin crop planning according to the protocol proposed herein.

2.0 COMPONENTS OF THE CROP-PLANNING PROCESS

2.1 Overview - Determining and Linking Forest-Level Objectives to Field Applications

A forest is usually managed to produce a sustained supply of goods and services to fulfil anticipated demands. A forest consists of many stands of different ages, sites, and species, and is defined more as an administrative (i.e. management unit) than as a biological entity.

The utility of the crop-planning process (Figure 1 and Appendix A) is first in determining and linking forest-level objectives to stand-level activities. The major activities forecast at the forest level and applied at the stand level are harvest and silviculture schedules. The bridge between the complex forest and the actual forest stand that is manipulated is the "forest class". A forest class, sometimes called a treatment unit or stand type, is defined as a group of stands that react in a similar and predictable manner in terms of both natural development and silvicultural treatment. Thus, instead of analyzing a forest composed of thousands of individual stands, the stands are aggregated into a set of "large stands" or small homogeneous forests (the number of such forest classes for a forest in Northern Ontario might be in the range of 30-60). Silvicultural ground rules are developed during planning for these forest classes instead of for perhaps tens of thousands of individual stands.

The homogeneity within each forest class allows managers to forecast forest development using a stand yield curve and age-class structure to characterize a whole forest class. Stand growth (i.e., yield curves) drives forest dynamics. The key to crop planning is controlling stand growth by both harvest and silviculture strategies.

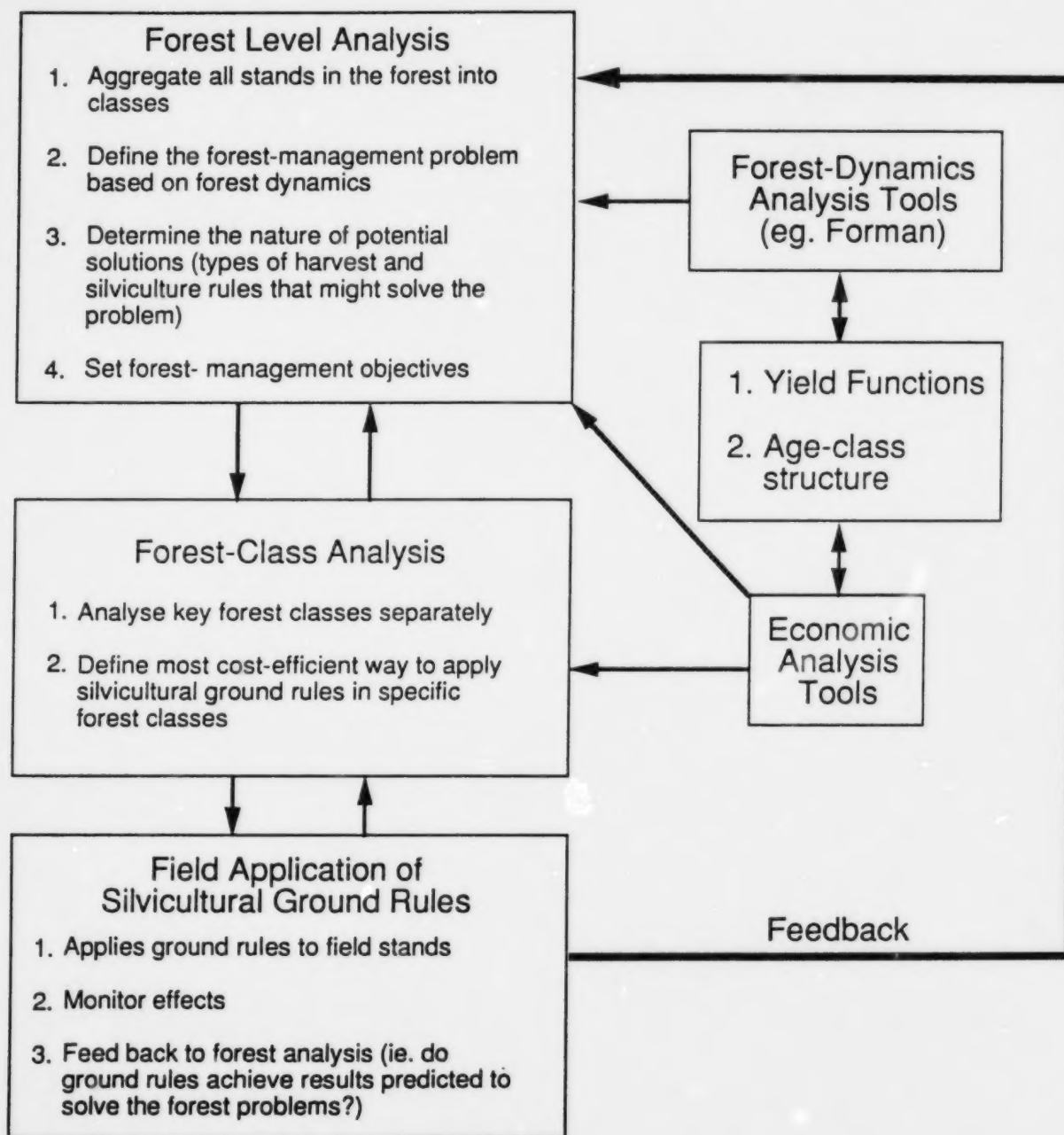
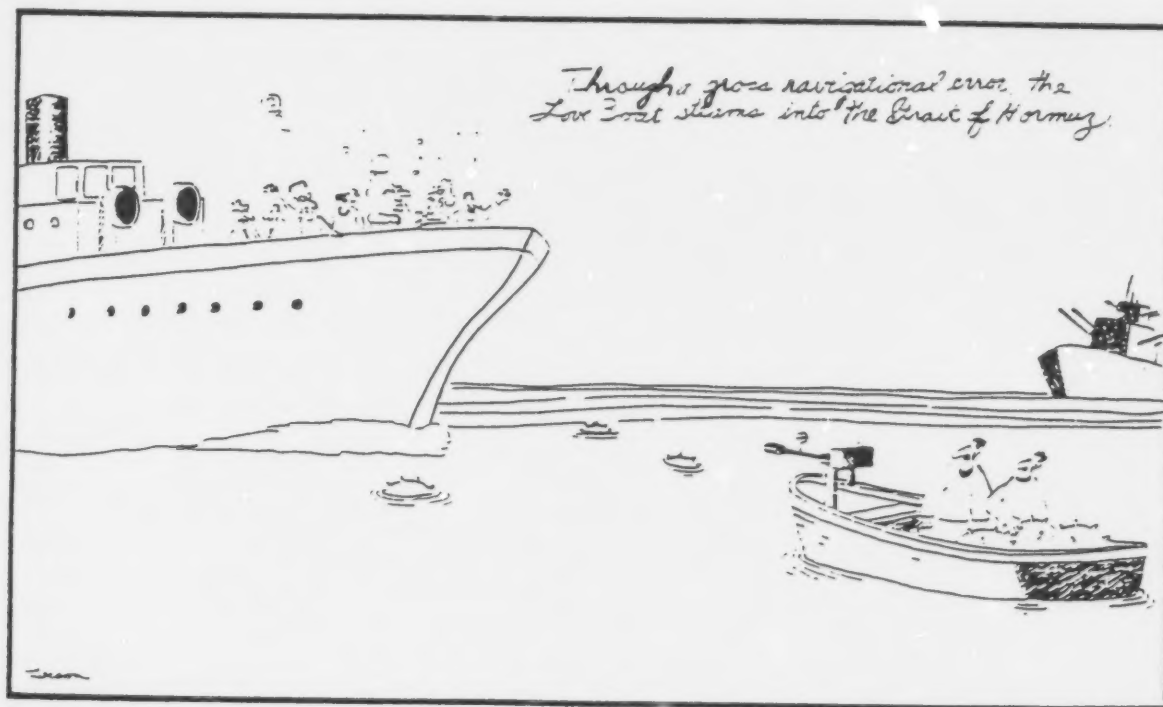


FIGURE 1. Components of the crop-planning process.

For each forest class, there may be several silvicultural options. Implementation of each option results in a unique growth pattern for that part of the class that is treated. A key challenge in crop planning is to first select the required growth pattern (i.e. represented by yield curves) for each forest class so that forest-level objectives are met at the most reasonable cost.

The purpose of the forest-class analysis is to determine the most cost-efficient silvicultural strategy or ground rule for each forest class that causes it to grow in a manner which will achieve the forest-level objectives. Key factors determining the cost of the silvicultural strategy are type and intensity of treatment. For example, artificial regeneration by planting normally costs more than natural regeneration per unit area regenerated or per unit wood produced. Also, in intensive treatments like planting, the more trees established, the higher the cost.

Implementation of a crop plan occurs at the stand level and consists of applying the strategy established previously for the forest class to which each stand belongs. Monitoring stand growth provides feedback to compare expected stand growth with actual results. Accurate monitoring of both stand growth and harvest patterns provides an error-detection process to link back to the forest level. If stands grow and harvest and silviculture patterns are implemented as forecast, the forest-management problem should be solved. If forest-level objectives are not being achieved, either the strategies were inadequately implemented or the basis for forecasting forest response was incorrect. In either case a review of management design is necessary. Like a ship (Figure 2), a management unit needs regular course changes or the captain will end up on a reef!



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FIGURE 2. Like a ship on an ocean, forest management needs direction and regular "course" changes based on new revised knowledge or it will end up with inappropriate results.

2.2 Sustainability - A Goal in Crop Planning

Crown forests are managed to benefit the citizens of Ontario. Most forest-management costs are borne by the Provincial Treasury, so the public expects to receive, directly or indirectly, the benefits of such management. Some tangible benefits from forest management include continuous availability of timber, wildlife, and recreational opportunities.

The forest manager considers not only the quantity of each benefit available now, but also how the quantities may change over future time. Through forest management, the forester regulates the flow of values that are available from the forest over time. Of course, there are limitations to what can be obtained, since the potential productivity of the forest depends on its size, the dynamics of its component stands, its site potential, the funds available for management, and any other limitations on management.

Sustainability is a common objective in forest management. Specifically, foresters want to design forests that can provide an "even flow" of products on an annual basis. This approach allows the development of a relatively stable industry that may still have slightly varying annual product demands from the forest due to markets. Therefore, a forester designs a forest for an "even flow" of products but allows deviations for market fluctuations.

One of the easiest ways to achieve sustainable levels of timber harvest is to organize the forest so that there is a roughly equal forest area in each age class for each stand type. In such a case, the oldest age class would be cut in each period, regenerated, and by the next period, an equal-sized forest area would have reached harvest age. In this manner, with perfect regeneration and stand development, a steady-state forest would exist, and consequently the flow of products would be even over time. This is a very attractive

proposition, and achievement of a regulated forest has remained a key goal of forest managers for a long time. However, natural forests are rarely in this balanced state. Thus, in most cases, a completely balanced, even-flow option never exists when forest management is initiated. In fact, the road to regulation is characterized by a substantial period of transition with more or less variable annual yield, either in quality or volume or both.

The challenge to many forest managers is to design strategies to convert existing unbalanced forests to regulated forests with a minimum disruption of forest uses. A traditional approach to regulating a forest is to determine the age of the oldest stand that would be found in the regulated forest, call it "R" years, and then each year cut $1/R$ -th of the total forest area. After R years, the forest would be regulated. Since this approach often results in uneven flows of benefits from the forest, its strict application is often unacceptable.

An alternative approach is volume regulation, i.e. harvesting an equal volume each year. If the chosen harvest is related to forest structure, then volume regulation will also eventually produce a regulated forest although not as quickly. In either case, it will be at least R years before a fully regulated forest is attained.

Clearly, a combination of area and volume regulation will usually be most effective in transforming a "wild" forest into a regulated one. In Ontario, the area-regulation process allows a harvest acceleration to occur if the average age of the forest is substantially greater than the average age of the target regulated forest. This does not allow one to observe how the volume flow would behave, so we suggest that a volume-flow analysis should accompany an area-regulation analysis. In this way, the forest managers can follow the volume/area-harvest relationship, not just the area-harvest pattern, which

describes only half the picture that a manager should see in establishing a smooth path toward sustainability.

In the examples described later in the report, volume-flow patterns under area regulation, and harvest-area patterns under volume-flow regulation, will both be shown. This will allow a fuller appreciation of the interplay between harvest volume and area.

2.3 Forest-Level Analysis - Determining the Forest-Management Problem, and Setting Crop-Production Objectives

Crop planning is forecasting future harvest and silviculture strategies that will produce the desired benefits (i.e. will meet forest-management objectives) from the forest. Forest analysis, based upon forecasts of forest-level dynamics, determines a range of feasible timber-production possibilities for the forest, from which an objective can be chosen. In this analysis, a "problem" exists if forecasts of benefit flows without management action (e.g., harvest without silvicultural investments) are insufficient to meet forest-management objectives. Specifically, the analysis outlines the future forest structure and dynamics which limit the temporal and spatial availability of forest benefits.

Forests in Northern Ontario are comprised of thousands of stands that can be aggregated into perhaps 30-60 forest classes. Each forest class can be characterized by similar productivity, stand type, and patterns of response to disturbance and intervention. Development of each class can be forecast using a growth curve.

Two general approaches can be used to design solutions to forest-management problems. One is to propose a strategy, simulate its effects over future time, then modify the strategy based on analysis of the simulation, and run another simulation. In this way, the forester can search until the first successful strategy is derived, or additional simulations can be made in an attempt to find improved versions. This is called an heuristic or self-teaching approach, and while the "best" strategy may not be found in such a trial and error process, the forester will understand the basis and nature of the solution chosen. This understanding is achieved because in this approach, the forester must propose the initial strategy and each subsequent modification. Thus, the outcome will depend, in large measure, on the skill and knowledge of the forester.

The second major approach emphasizes use of optimization techniques. Here, using the same description of the forest and the same yield curves as in the first approach, special models determine an optimal management regime based on maximizing or minimizing specific features of production. Obtaining an optimal solution is an advantage of this approach, but optimization models do not offer easy comprehension of dynamics, so it is difficult for a forester to judge why the optimal solution is in fact optimal. Secondly, when a manager faces a number of different objectives, it may be awkward to set up an optimization model in a suitable manner. The plans produced by these models are hard to understand and implement, and require considerable faith in the underlying premises and assumptions.

Both approaches have advantages, and both can be useful planning aids at the forest level. In the examples presented in this report, the simulation approach was used. The emphasis in this paper is on learning about forest

dynamics while solving wood-supply problems to gain comprehension of control over forest dynamics. Not dealt with but also potentially solvable using either simulation or optimization approaches are other forest-management problems such as habitat shortages and budworm susceptibility. Ultimately, all these problems can be dealt with through application of a crop-planning process.

To determine or solve a wood-supply problem, it is suggested that the forester proceed by posing the following questions:

- * What is the wood volume required from the forest based on present and future demand?
- * What long-term sustainable levels of merchantable volume can be harvested from the forest without any silviculture?
- * What is the range of production possibilities and what is the biological basis for each of these?

A forest simulator such as FORMAN (Wang, Erdle, and Roussel 1987) is the tool used to identify and analyze wood-supply problems and their biological basis. If natural regeneration can sustain the harvest levels required, then no silviculture input or modification of harvest queue (or sequence) is required. If there is a deficiency, the challenge will be to determine the strategies that will provide, at the right times, the wood required. The forecasts will always be a function of the unique forest dynamics and the harvest and silviculture schedules applied.

Crop-planning solutions are designed by determining the sequence of stands to be harvested, and the sequence of stands to be treated silviculturally over the forest-management planning period. Harvest timing of each stand is based on the yield curve that represents its growth pattern and the need for the stand to be harvested to achieve forest-management objectives. The position of the

stand in the harvest queue can sometimes be changed by altering the stand's development pattern (yield curve) through silvicultural input.

2.3.1 Forest Development

A fundamental basis for understanding forest development in the crop-planning process is the association of an age-class histogram with an appropriate yield curve for each forest class, as in Figure 3 (Baskerville 1979). The forest represented in Figure 3 is a 100,000 ha single-species (balsam fir) forest consisting of one site class. Hence, this forest is actually a single forest class as defined in this report. In analysis of a real forest, yield curves and age-class structures would be required for all forest classes.

The forest represented in Figure 3 is developing over time without harvest. The age-class structure changes as time goes on as a result of stand aging. Indicators of forest-level changes shown in Figure 3 include annual harvest, total growing stock, and the annual growth rate of the forest. Thus, indicators of forest development (e.g., growing stock, and increment) change even without man's intervention.

With time, the forest develops from one dominated by slightly overmature stands (generating a negative increment) with decreasing overall growing-stock volume, into one where the overmature stands have regenerated into fast-growing young stands, resulting in positive forest growth by year 80 in the future. Harvesting would have accelerated this process by removing decadent stands earlier.

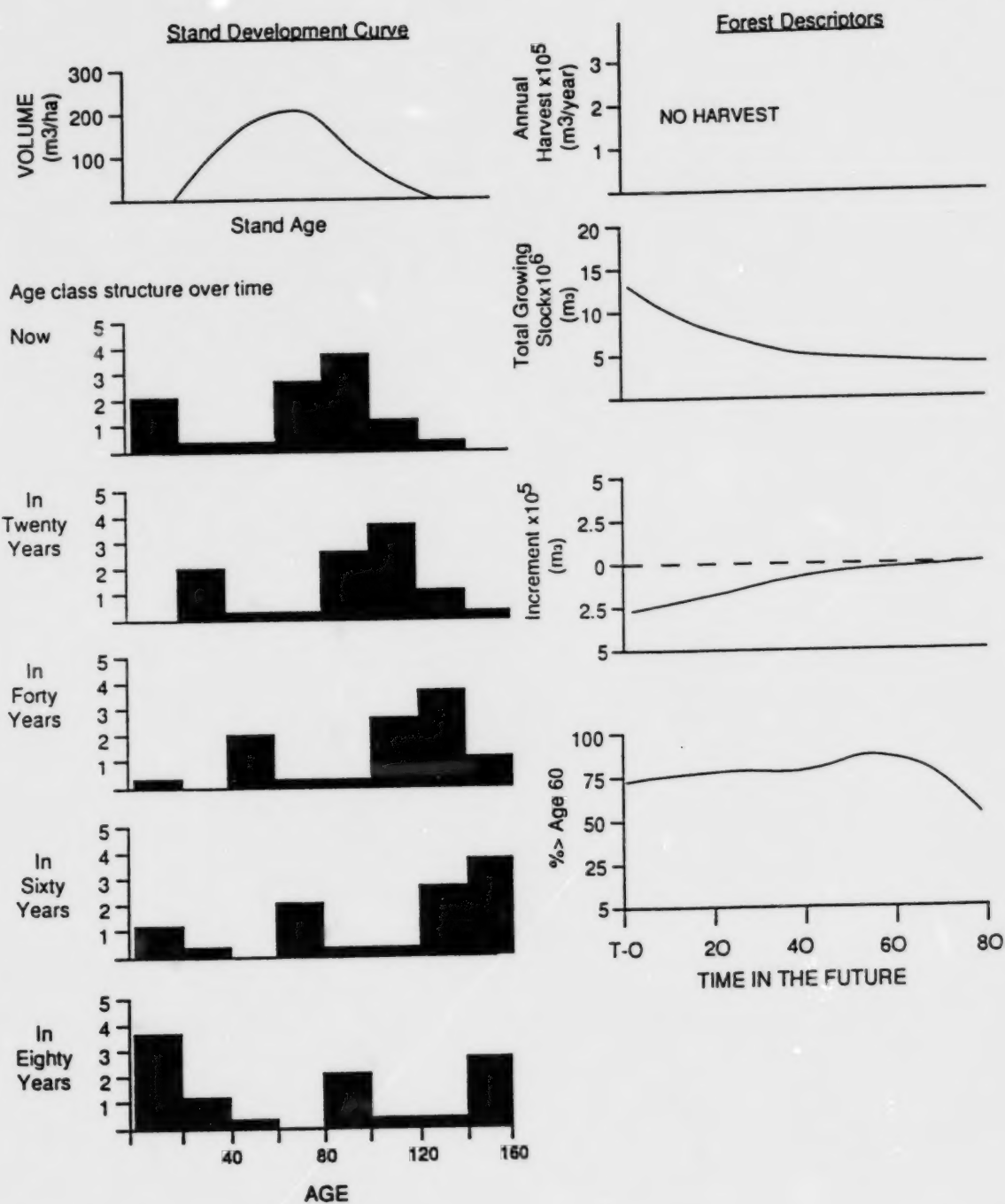


FIGURE 3. Development of a balsam-fir stand over time (Baskerville 1979).

Other indicators can also be used, depending on the forest-management problem to be analyzed. For example, if stand conditions required by moose can be formulated into a "moose-habitat yield curve" for each forest class, the potential moose carrying capacity of the forest could be tracked over time. In general, a number of forest-level indicators should be displayed simultaneously in analyses of forest dynamics to reduce the risk of drawing invalid conclusions based on one indicator used in isolation.

To summarize, initial forest-level analysis is undertaken to determine a wide range of production possibilities and the silvicultural strategies associated with each. We encourage use of a forest simulator such as FORMAN which allows a large number of classes. The minimum data required by FORMAN are age-class histogram and present and future yield curves for each forest class identified. Outputs from each simulation can be summarized in graphs and charts as in Figure 3. Implementation of many simulations, where the forester experiments with different yield curves that represent specific silvicultural strategies, will generate both (a) the range of production possibilities from which to choose an initial production objective, and (b) increased understanding of how harvest and silvicultural strategies alter dynamic forest structure and production.

2.4 Forest-Class and Final Forest Analysis

2.4.1 Developing Cost-efficient Silvicultural Strategies (Ground Rules)

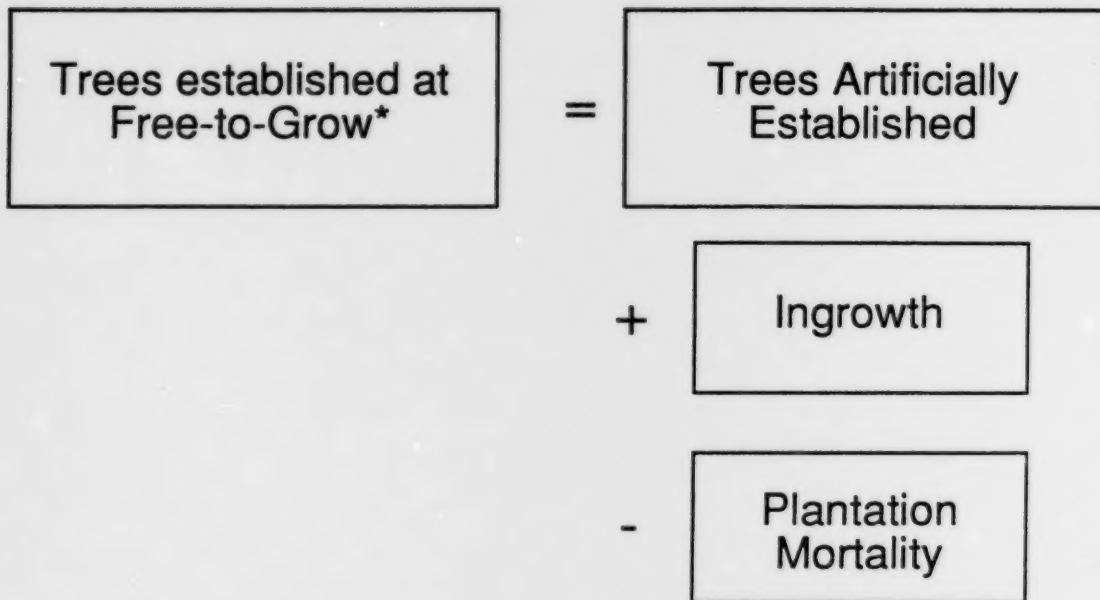
The initial forest analysis leads to definition of the forest-management problem in terms of control of forest dynamics and indicates the scope of harvest and silviculture strategies that should solve it. The forest analysis

is driven by stand yield functions representing each of the forest classes in the forest.

Forest-class analysis abstracts each class from the whole-forest context to permit more detailed examination of alternative management strategies. It allows the determination of the most cost-efficient silvicultural option or strategy which can cause stands to track along the yield curves found to be desirable in the forest-level analysis. The tool used for this evaluation is benefit-cost analysis, as discussed in Section 2.7.

A key variable in determining cost-efficiency of the regeneration objective is the density or spacing regime. The regeneration possibilities, expressed in terms of stand density (i.e. number of well-spaced trees per hectare at free-to-grow), depend on number of trees artificially established, natural regeneration, and seedling mortality (see Figure 4). A stand density expressed in well-spaced trees per ha also implies an average spacing regime (i.e. average distance between trees). For purposes of this report, density objectives will be expressed as spacing-regime objective (e.g. 2.5 m spacing instead of 1,600 well-spaced trees/ha).

Stand spacing regime not only affects silviculture cost but also growth characteristics (e.g. time of harvest, piece size, and wood quality of the stand). This implies that the yield curves used to analyze the forest-management problem in the initial forest analysis may be modified during the forest-class analysis. Would it not be more efficient to use these curves in the initial forest analysis and save a couple of steps? Certainly, various spacing regimes could be compared in the initial forest analysis. In fact, the silvicultural strategies applied to the forest classes in the initial analysis



*Well spaced trees/ha at a predetermined spacing regime

FIGURE 4. Determination of regeneration density. If the number of trees per hectare at free-to-grow deviates from the regeneration objective, additional silvicultural treatment is needed.

assumed a specific spacing regime. However, if there are dozens of forest classes and 3 to 4 spacing regimes for each, the forest analysis becomes onerous and selection of the most favourable silvicultural strategies less likely.

Why not determine the most cost-efficient spacing regime (and thus yield curve) before the initial forest analysis, thereby requiring only one forest analysis? The solution to a forest-level problem is rarely the sum of the "best" stand-level actions as determined at the stand level - "best" stand treatments determined in the forest context usually differ from the "best" treatment determined for each stand individually. Also, without the initial forest analysis one would have no idea of the biological nature of the forest problem to be solved nor what silvicultural strategies could solve the problem.

Appendix B outlines the effects of spacing regime on stand growth, silvicultural costs, and timing of harvest, and Appendix C outlines the effects on wood quality. Understanding these effects is critical before attempting to apply different spacing regimes to forest classes.

2.4.2 Final Forest Analysis

Once the final yield curves and associated silvicultural options are determined based on cost-efficiency, a final analysis using a forest simulator such as FORMAN determines the most cost-efficient harvest and silvicultural schedules that will solve the forest-management problem and thus provide the required forest benefits at lowest reasonable cost. It will also determine forest-level costs and benefits associated with this forest management strategy.

2.5 Understanding Stand Growth

2.5.1 The Yield Curve

Forest-class development represented by stand yield functions and associated age-class structure determines forest dynamics. Control of these elements is vital to effective crop planning. Control of actual stand growth is predicated on developing the most accurate stand-yield forecasts based on biologically correct assumptions. To do this, a forester must have a clear understanding of growth patterns and their inherent biological principles.

A stand is a community of trees with a structure that can be manipulated to produce required products and services. Baskerville (1962) said, "One of the major objectives of silviculture is the manipulation of forest stands to control the quality and quantity of useful material produced." Important influences on stand development are species composition, stand density, site productivity and genetics (Baskerville 1962; Assmann 1970). Productivity is based on physical site characteristics which influence the relative amounts of moisture and nutrients available and the amount of sunlight that reaches the site due to aspect, slope and latitude.

Every site and species combination has an innate biomass production capacity or yield (Nawitka Resource Consultants Ltd. 1987). This equilibrium or carrying capacity is reached when a site is fully occupied by trees (Baskerville 1962). Full occupancy or site utilization occurs when a site has the maximum amount of biomass that it can support. After full occupancy, the amount of crown or foliage area remains relatively constant (although the number of trees diminish) and thus, biomass production remains relatively constant (Mar:Moller 1947; Baskerville 1962).

For purposes of illustrating these concepts, the following paragraphs outline the stand dynamics of planted (low density) even-aged, single-species conifer stand. Baskerville (1986) defined stand dynamics as how trees actually perform in a community of trees subject to competition for sunlight, soil, nutrients and water.

Figure 5 graphically represents a yield curve that shows the development of a typical forest stand (e.g., managed plantation) and all of its phases. In Figure 5, development is gauged in terms of height, total volume, current and mean annual increment (CAI and MAI, respectively), and number of trees per hectare. The yield curve in Figure 5 assumes that the site eventually becomes fully utilized by the trees within the stand.

When a plantation is established, there is little intraspecific competition for the available site resources. Alternatively, in a dense natural stand, the reverse is true - inter and intraspecific competition results in significant mortality. In the newly established plantation, the crop trees incompletely use the available water, CO_2 , nutrients and sunlight to produce carbohydrates (wood fibre). Where weeds exist, interspecific competition occurs as the non-crop plants quickly grow and lead to full use of sites resources. In the latter case, if weed control is carried out, the CAI of desired wood fibre increases. During the latter period of this phase, the roots begin to overlap for many species. Fayle (1975) found that red-pine trees had extensive root overlap by age 6 to 10 years in plantations spaced at 2 metres. Baskerville (1962) cited authors who concluded that intense root competition occurs long before crown competition.

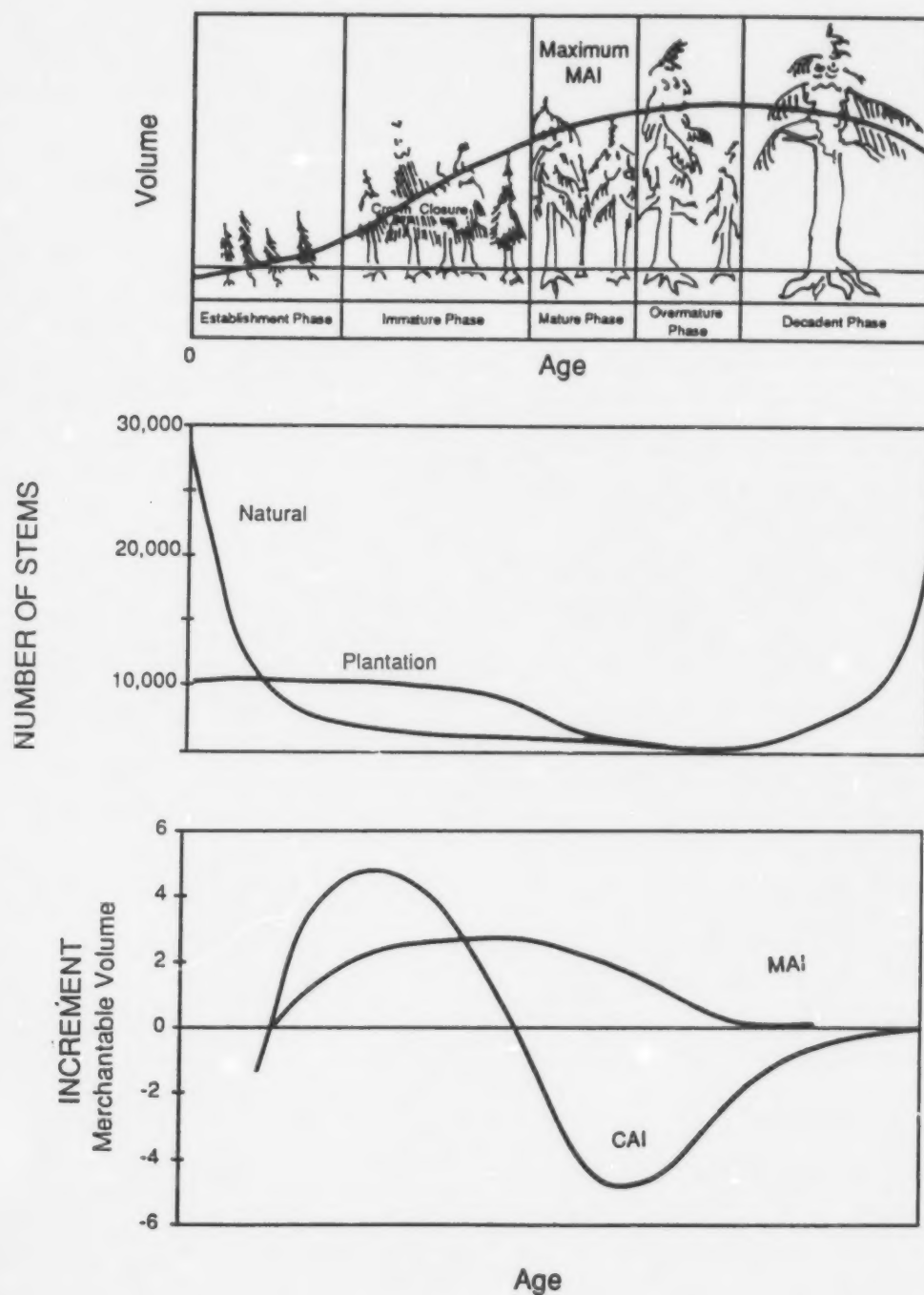


FIGURE 5. Some characteristics of development over the life cycle of a stand.

During the immature phase, crown closure can occur for many species. For red pine at 2 m spacing, closure commonly takes place between 11 and 15 years (Fayle 1975). At crown closure, neither full site utilization by the trees nor maximum annual growth of either roots or stems has occurred. Roots and crown continue to increase in surface area until the available resource space is occupied (Fayle 1975). Maximum CAI (current growth - current volume loss) eventually occurs when exploitation efficiency of root and crown space has maximized and full site utilization has occurred. Normally, significant interspecific competition from shrubs and non-woody vegetation ends during this stage.

Full site utilization by the trees of any given species within the stand may mean crown closure and full soil exploitation by the roots. However, for some species (e.g. jack pine on a sandy site) crown closure may never occur but the site is fully utilized. In balsam fir stands on some sites, crown closure may have occurred but full root exploitation of soil may not occur (Baskerville 1990). The key is that, at full site utilization, the site is producing the maximum biomass possible based on the species present and inherent site productivity. Once full site utilization is achieved, intraspecific competition becomes intense resulting in dominance by certain tree individuals, suppression of others, and tree mortality. In natural stands (Figure 5) significant mortality occurs long before this stage because of the huge overhead of initial stems.

At the beginning of the mature phase, average growth per year over the life of the stand, or MAI (average growth minus average volume loss), is maximum. This is normally when foresters consider the stand eligible for harvest as it represents the point where maximum volume production per unit time from a site occurs. The intense competition during this stage triggers mortality of suppressed trees within the plantation. Continued growth of dominant trees, which require more of the site's finite resources, results in further suppression and mortality of smaller trees. Although this stage is characterized by a declining CAI, current volume increment is still greater than volume lost through mortality and there is a gradual increase in standing volume.

The overmature stage is also called the "holding stage." Here the current growth is equivalent to the volume lost through mortality. The dominant trees are getting still larger and may become more suitable for sawlogs. The growth of younger trees in the understorey is unlikely to help maintain the total volume. Finally, the decadent stage is characterized by a decline in stand volume (negative CAI), where the current growth is less than the volume lost through mortality. The dominant trees, nearing the end of their life cycle, may still be growing larger and demanding more resources, but at a reduced rate. Mortality is the major factor and the volume/ha is decreasing at an accelerating rate. In two boreal studies, the drop in merchantable volume per hectare was very dramatic for decadent black spruce (Willcocks 1977; Wood and Beckwith 1987).

2.5.2 The Need for Biologically Sound and Accurate Yield Curves - A Key in Solving Forest-Management Problems

Stand yield drive forest-level dynamics, and improvements in stand yield as reflected in the yield curves should result in better management decisions for the whole forest. Crop-planning accuracy, and thus solutions to forest-management problems, is dependent on how accurately the stand yield curves and the evolving age-class structure represent actual development in the forest over future time.

Some stand yield curves based on field measurements are available for use. Baskerville (1989b) felt that present growth and yield work reflects an emphasis on fitting stand-development data to achieve statistically sound and precise curves rather than evaluating biological accuracy.

Common among foresters is the statement that there are no data available for forecasting stand response to treatment. Such an assertion fails to recognize that all treatments are made on a presumption of response. Others suggest that making yield curves based on sound biological knowledge is acceptable and the only defensible way to forecast future stand growth (e.g., Baskerville 1989b). Baskerville (1989b) stated "if we wait to get data, we won't need it" (i.e. the forest industry may collapse before we solve the problem or just that the problem will have changed). More importantly, the stands in a forest will already have "developed" into a "new" set of stands for which we still will have no data. Baskerville (1989b) recommends that "rather than concentrate effort on data for managed stand yield tables, the course of forest management would be better advanced by achieving greater biological realism in stand growth modelling generally." Current emphasis on data collection and using mathematical models to discover already known biological

facts (re-inventing the wheel) has prevented us from using growth and yield basics to design biologically realistic forecasting models that could be modified based on data collected from field monitoring.

Types of Yield Curves Based on Biological Realities

Constructing yield curves for crop planning requires knowledge of the basic biological growth-and-yield principles outlined previously, as well as local knowledge of the forest and whatever data is available. This knowledge and experience can be used to hypothesize growth forecasts for a range of treatments and sites (Figure 6a and 6b). Wherever possible, the curves should be calibrated with growth-and-yield data.

Critical to crop planning and its ultimate goal of solving forest management problems, is finding an implementable stand yield curve (and associated treatment) that will apparently solve the forest-management problem. Forest analysis is sensitive to yield curve shapes. For example, a wood shortage forecast to occur in 40 years in a specific forest will require management input that will produce stands that will yield operable volumes within 40 years. In such a case, the forester would probably choose yield curves reflecting spaced natural growth rather than planted or natural stands to solve the supply problem (Figure 6b). Treatments reflected by spaced natural curves can produce harvestable wood in a shorter time span than the others. However, it is not biologically reasonable to expect a spaced stand to produce significantly more volume than a natural stand once the site is fully utilized.

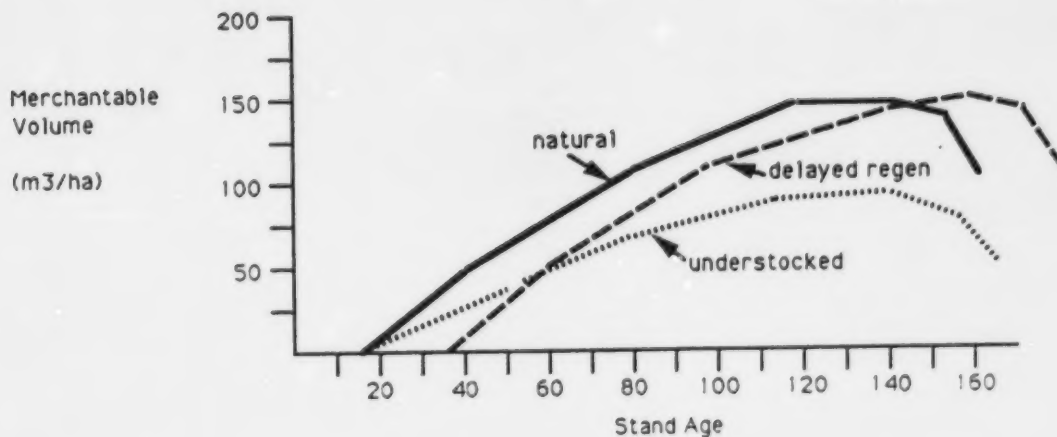


FIGURE 6A. Poor regeneration takes some combination of two forms of response: a) delayed regeneration that achieves full stocking, and b) timely regeneration that is understocked. The difference is important to management design (Baskerville 1989b).

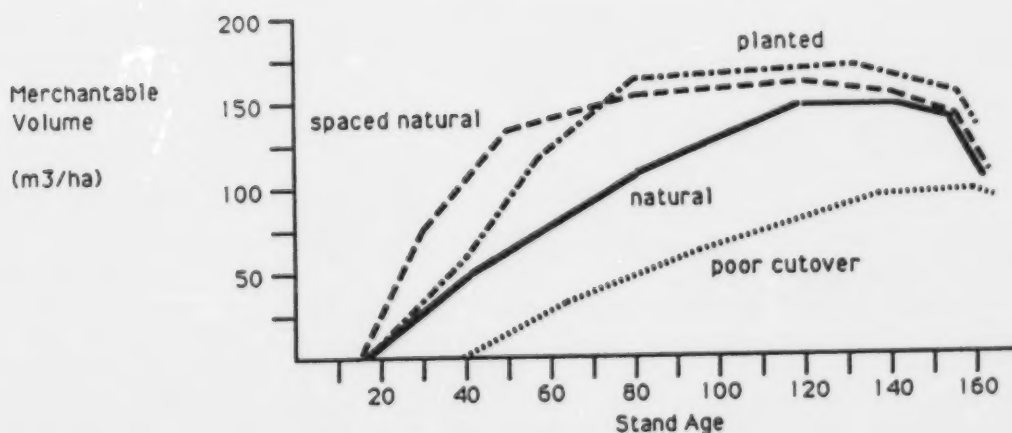


FIGURE 6B. Comparison of the shapes of yield curves for one stand type subject to different treatments (Baskerville 1989b).

Where Errors in Yield Curve Construction can Invalidate a Crop Plan?

Sensitivity

What is the effect on forecast forest dynamics if there is a yield curve error? Obviously, most managers hope that large differences between forecast yield curves and yield performance in reality are uncommon and do not seriously effect forest dynamics. However, sensitivity of a crop plan to error in yield-curve shape is a function of stand-development patterns, age-class structure, harvest rules, and silvicultural strategies for a specific forest, i.e., sensitivity to yield curve error is unique to each situation.

Figure 7 shows a forest, studied for sensitivity, that has 40 years of management control by harvest and silviculture schedules (Baskerville 1989b). The harvested areas were treated by silviculture schedules and the regenerating stands now follow one of the four possible stand development forecasts or yield curves.

In Figure 7:

- i) areas not yet harvested are still growing along original natural yield curves;
- ii) some harvested areas have regenerated naturally and the new stands are forecast to grow along the natural yield curve (shaded areas in first graph);
- iii) some harvested areas have regenerated unsatisfactorily into poor cutovers and these stands will develop along a yield curve with reduced volumes and delayed availability;
- iv) some harvested areas have been planted or pre-commercially thinned and these stands have higher yield forecasts and earlier availability.

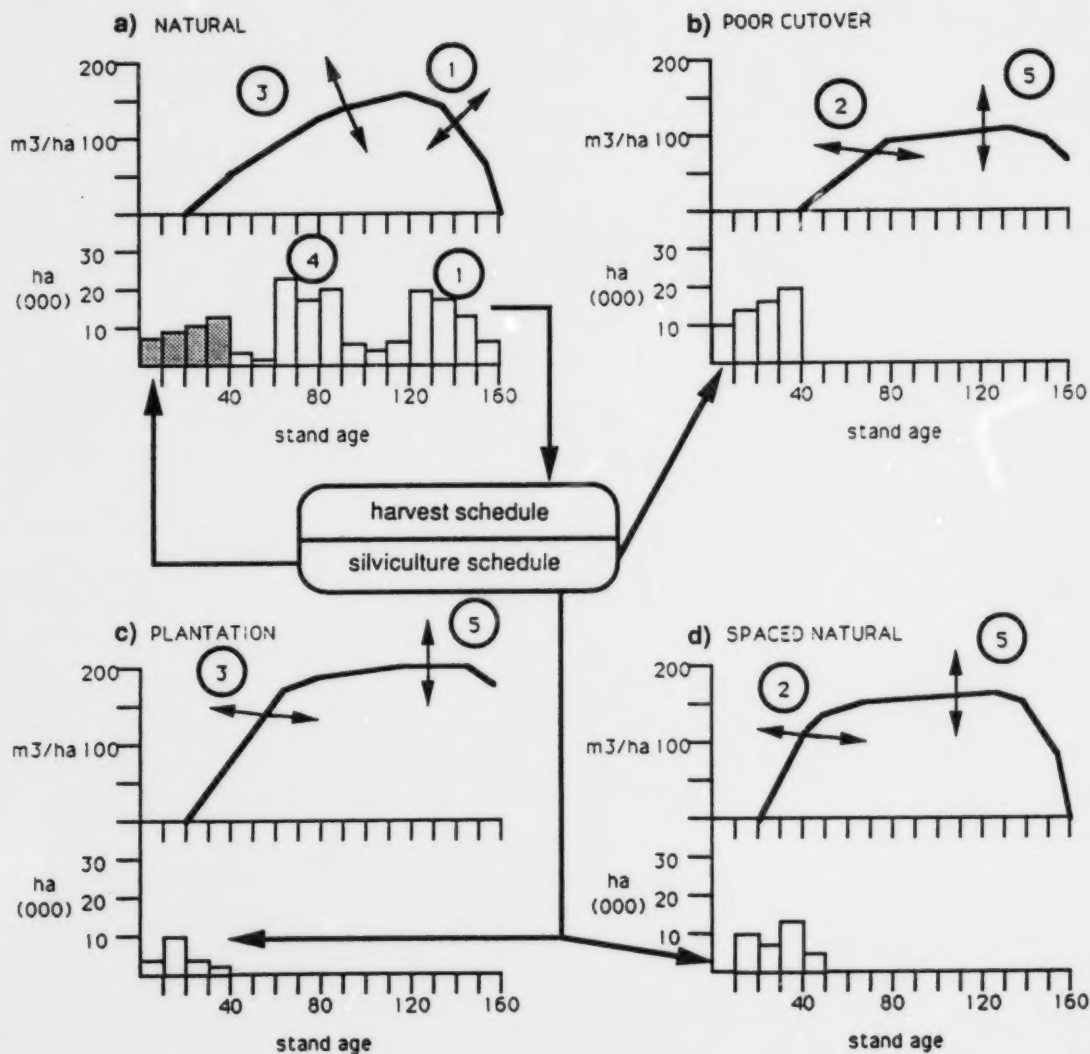


FIGURE 7. Sensitivity of forest management design to error in stand yield curves and the associated age-class structures (Baskerville 1989b). "1" means a small change in the circled part of the yield curve or age-class structure will cause a large change in forest-class response. On the other hand, "5" means only small changes will occur at the forest level with any changes in the circled part of the yield curve.

The sensitivity analysis, summarized in Figure 7, involved making systematic changes (errors) in the stand yield curves to see the results at the forest level. The circled numbers on segments of the yield curve or age-class histogram show sensitivity, where "1" means a relatively small change in this segment of the yield curve or any age-class structure will make a disproportionately large difference in the forest level forecast. Alternatively, "5" means change contributes little to the forest level outcome. For example, in Figure 7 (top left graph) slight changes in volume loss and changes in the area of stands in the 120-160-yr age classes will have a significant impact on the maximum sustainable harvest (sensitivity value of 1). This is largely due to selection of the oldest-first harvest rule in this sensitivity analysis. The curves for spaced natural stands and plantations (lower graph) have a low sensitivity rating of 5 at the older ages in this case. This is because few, if any, of these stands will be harvested at this age during the transition to a regulated forest. Yield-curve sensitivity analysis flags the priority areas where yield studies (i.e. monitoring) should occur.

Variable Density and Variable Species

Most yield curves assume single-species stands of one density. For forest managers, this represents an oversimplification of their forests, since most forests consist of stands that are multi-species and of varying densities. Appendix B is a literature review on the relevant biological factors associated with stand density. The crop-planning process identifies stand density as an important factor for determining cost-effectiveness, wood quality, and availability of a stand for harvest.

2.5.3 Stand Growth Parameters

The growth indicators, shown in Figure 5 can be quantified in yield tables by site productivity class. Indicators such as total stand production, gross total volume, mortality loss and merchantable volume are usually summarized in yield tables. Confusion with these terms is common among foresters (Nawitka Resource Consultants Ltd. 1987) and can cause problems when applying growth concepts to crop planning. Figure 8 shows that total stand production per ha to a point in time equals the total living tree volume standing at that point, plus volume lost to tree mortality, plus volume of weed trees. Crop plans normally aim to maximize the amount of merchantable volume produced and retained by minimizing the other components through density management, including weed control.

Gross stand merchantable volume is determined from the sum of merchantable volume of individual trees and is dependent on the minimum merchantability limits imposed by the crop planner. These are usually specified as minimum DBH and minimum top diameter.

Merchantability or operability of a stand is an economic determination (not biological) that depends on both minimum average size of trees that can be harvested economically and minimum merchantable volume per ha required. These merchantability limits are flexible and are important because they determine the minimum stand age of harvestability. For example in Figure 9, if the minimum operable volume per ha has been set at 50 and the tree size must represent at most 15 stems per m^3 , then the stand would be operable from age 46 to 112 years. Before age 46 and after 112 years, there is merchantable volume within the stands, but not at a cost-efficient operable level.

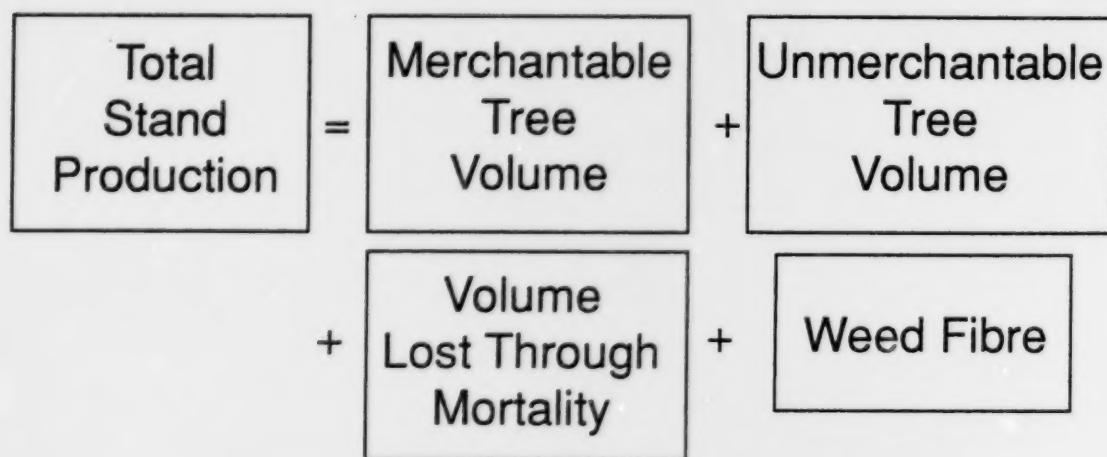


FIGURE 8. Total stand production equation to a point in time.

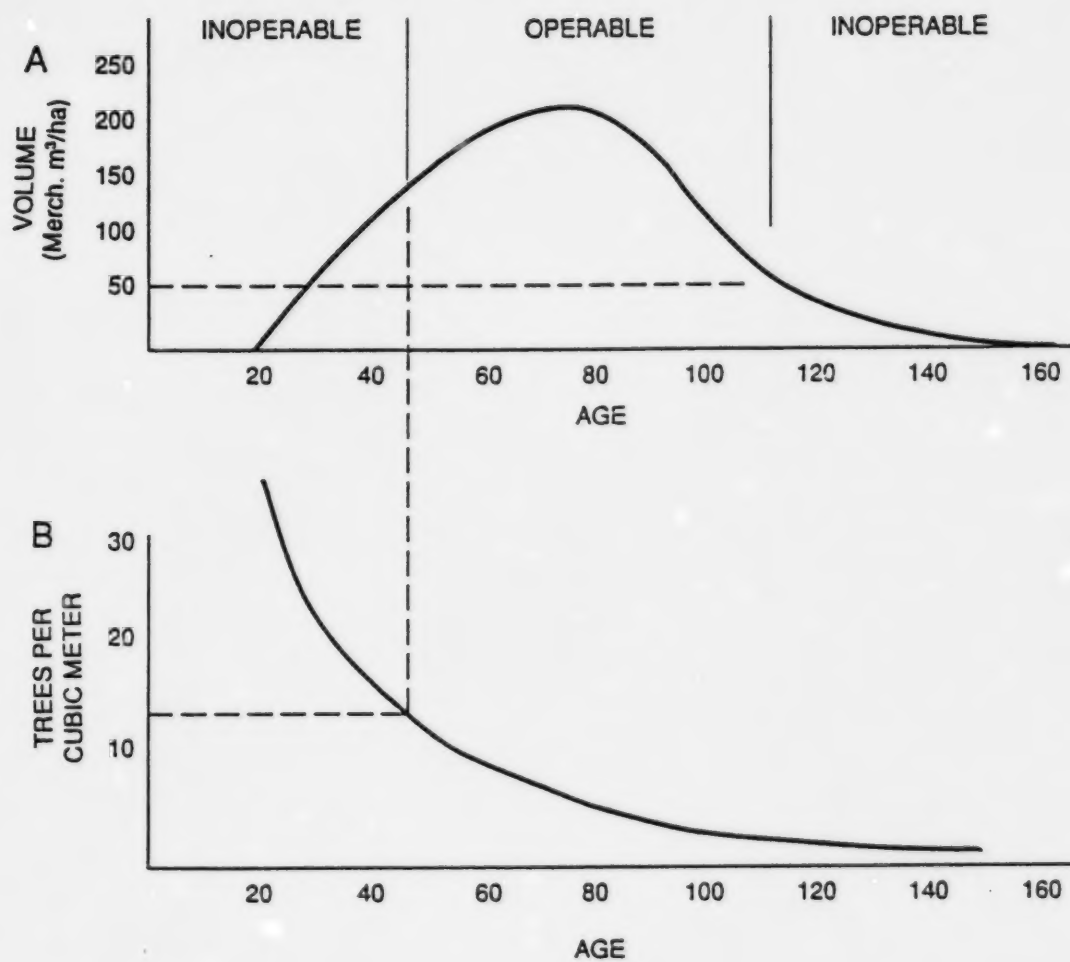


FIGURE 9. The influence of volume and tree size on forest stand operability. See text for explanation (from Baskerville 1979).

2.6 Field Application of Silvicultural Ground Rules

Silvicultural strategies or ground rules determined for each forest class in the context of a particular whole forest provide a unique bridge between planning at the forest level and actions taken at the stand level. A stand is categorized into one of the forest classes, and stand prescriptions that are directly linked to the forest needs are implemented. This approach contrasts with the traditional approach where each stand is evaluated (treated) separately, out of the context of influence on the achievement of forest-level objectives.

Once silvicultural ground rules are determined and the silviculture is implemented in designated stands in the forest, field monitoring should provide data for accurate evaluation of the yield curves used in the forecasting. Monitoring allows managers to detect error in the assumed stand and forest dynamics and to revise the treatment schedules to maintain integrity of the forest-management plan. This feedback loop provides the manager with a continuous application of adaptive management.

Effective application and monitoring of silvicultural ground rules requires explicit field targets or regeneration objectives that in practice are achievable and understandable by field staff. For example, a common failure in meeting a spacing regime or density objective results from the amount of natural regeneration that occurs. Ingrowth affects the number of trees (and cost) that must be artificially established to achieve the objective, and can invalidate a planting strategy by causing a young stand to be either too dense or too sparse.

For crop planning to be accurate and cost-efficient, an ability to forecast both natural regeneration by forest class and stand dynamics is critical. Evaluation at the free-to-grow stage is required to determine the natural-regeneration component of the regeneration-objective equation. Over-planting (or excessive ingrowth) has a number of detrimental consequences. For example, Dunsworth (1979) found that in MacMillan-Bloedel's British Columbia coastal operations, more than 57% of their 9-19-year-old plantations were overstocked. Some of the detrimental consequences are:

- * money was wasted by planting too many trees;
- * forecast crop volume would be inaccurate (higher) because the wrong yield table was used;
- * forecast crop piece size would be inaccurate (lower) because the wrong yield table was used;
- * forest-level objectives would ultimately not be achieved.

2.7 Economic Analyses

2.7.1 Forest-Class Economic Analysis

Economic theory, as first described by Faustmann (1849), is based on costs and benefits applied to a unit of "bare" land. It evaluates an investment based on the funds invested and benefits returned on the same piece of land or in the same forest stand. With respect to a forest consisting of many stands, it is important to recognize that the forest-level return on investment is not simply a sum of the economic performance of individual stands. The reason is that each stand harvest decision is not independent of conditions in other stands; it is conditioned by the unique forest dynamics and the harvest and silvicultural strategies required to provide the desired benefits from the whole forest. Stands are scheduled for harvest as needed in the context of wood flow from the

forest. For example, the highest investment return from an individual stand may be obtained if it is harvested at age fifty, but in an overmature forest the harvest schedule may call for the stand at age eighty (or forty), thus making the single-stand economic return parameters meaningless.

The absolute values from a stand or forest-class economic analysis are not relevant at the forest level but they can be used to discriminate among various silvicultural options or spacing regimes for forest classes. Appendix D describes the various economic analysis tools available.

2.7.2 Forest-Level Economic Analysis

In the initial forest-level analysis, a maximum sustainable harvest level in the absence of silvicultural treatment is determined. If this level is lower than the desired level, calculations are made to determine the nature and future timing of the constraint which prevents sustainability of the desired harvest level. Silviculture is then planned and implemented to relieve the constraint. Even though the stands silviculturally treated are not available for harvest until some future time, the sustainable harvest from the whole forest can be higher for the whole forecast period than the no-silviculture level. The difference between the even-flow sustainable yield without silviculture, and that with silviculture, is called the allowable cut effect (ACE).

Although most silvicultural treatments (e.g., planting) do not normally yield tangible benefits immediately from the stands in which they are implemented, ACE shows that, in the forest-level context, silviculture applied today can yield immediate increased forest harvest levels consistent with a long-term sustainable yield. Economic analysis of the cost-efficiency of silvicultural strategies at the forest level (see Appendix D) makes a basic

comparison of the value of annual harvests and the costs of annual silvicultural treatment.

Not all investments in silviculture are made to capture an ACE. Sometimes the sustainable harvest level without silviculture is sufficient to meet desired wood flows, but managers choose to invest in silviculture to be able to raise the harvest level at some future time. In all the examples we present in this report, we assume that maximum ACE is desired. This assumption greatly facilitates forest-level economic analysis, as the annual expenditures in silviculture can be directly compared to the monetary value of the annual ACE.

3.0 APPLYING THE CROP-PLANNING PROCESS

Three examples that illustrate application of the crop-planning process are given below. Even though they involve simple forests, they demonstrate the potential of the process in selecting cost-efficient management activities to achieve forest management objectives.

Recall that the general approach is to determine first the potential of the forest to produce forest-level benefits both with and without silviculture, leading to a definition of a forest-management problem. Management input in the form of harvesting or silviculture strategies is applied in a forest analysis to determine if the desired benefits from the forest can be achieved.

We used the simulation model FORMAN (Wang et al. 1987) to forecast forest-level dynamics and to analyze various solutions to forest management problems. Once the nature of the solution (i.e. yield curves) was determined at the forest level, a forest-class analysis was undertaken to find the most cost-efficient silvicultural options (ground rules).

The outcomes illustrate that the forest manager has considerable flexibility in solving wood-supply problems. The flexibility arises because more than one solution exists by varying harvest and silvicultural options applicable to a particular forest. The manager also has the opportunity to improve cost-efficiency by using benefit/cost analysis at the forest-class analysis.

The examples concentrate on wood-supply problems. Other forest-management problems range from managing moose habitat to controlling budworm susceptibility. Addressing these problems would involve different "yield" assumptions and possibly different economic tools, but the process components would be analogous (Figure 1).

Our examples are for illustrative purposes only. The solutions obtained are unique to the forests considered in the examples. The illustrations are meant to demonstrate the crop-planning approach and the inter-relationships of the components. The discussion does not represent a manual but rather a framework for problem solving.

(Appendix A is an outline of the steps in the crop-planning process and the assumptions used when it was applied in our examples. Forest managers are strongly encouraged to develop their own assumptions when implementing the crop-planning process).

3.1 Example One: A Black Spruce Forest on One Site Class Producing Pulpwood

3.1.1 Management-Unit Description and Objectives

The forest examined in this example is a 38,000 ha collection of Site Class 1A black-spruce stands. The age-class distribution is biased towards juvenile and old stands (Figure 10). Present stands are assumed to be developing according to a single, natural-stand yield curve (in our examples, we have employed yield curves assuming that the stands so described are fully stocked and well tended). In the examples, future stands not treated following harvest regenerate along the same natural forest yield curve, but with a fifteen-year regeneration delay. Variable density yield curves for managed stands are used to describe stands that are planted or pre-commercially thinned.

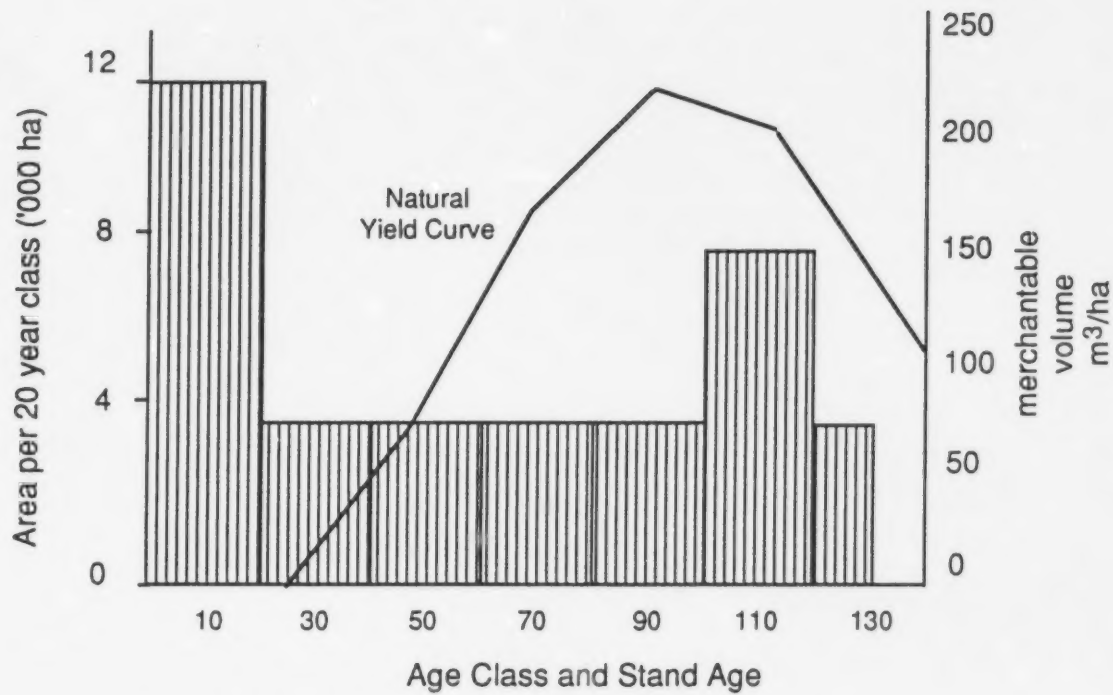


FIGURE 10. Age-class structure of the forests in Examples One and Two (age-class designations are midpoint ages).

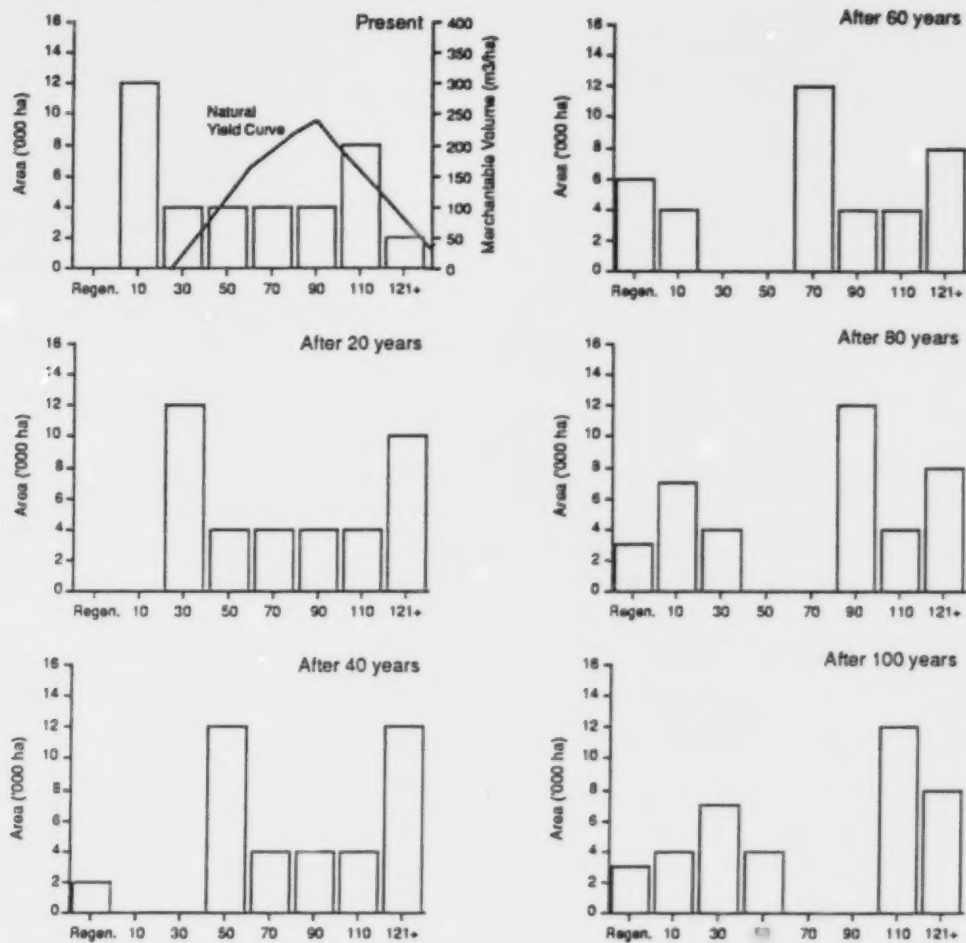
For a harvest to be considered sustainable, a constant volume must be obtained in each five-year period of a 100-year forecast and the growing stock must not be allowed to decline below 150% of the periodic allowable cut at any time. This growing-stock buffer protects against "error" between the forecast and the real harvest during any five-year period. The desired sustainable yield from this forest is 110,000 m³ per year. The product required is pulpwood, and stands must have a minimum average DBH of 15 cm before being considered operable.

3.1.2 Forest-Level Analysis - Determining the Forest-Management Problem

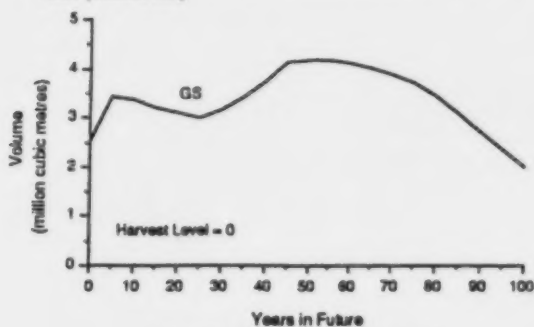
We simulated the development of the forest with no harvest to observe dynamics without intervention as a base case (Figure 11). The forest developed a preponderance of overmature stands and retained a large volume of growing stock over the forecast period. Such a forest has a high susceptibility to natural catastrophe such as fire or blowdown.

For comparative purposes, an area-regulation scenario with a rotation of 65 years was simulated on this forest. The five-year harvest area was set at $38,000/65 \times 5 = 2,923$ ha. It was also assumed that no artificial regeneration would be performed. Therefore, when area moved into the regeneration-delay phase, the time until harvest became 80 years. It was assumed that the allowable harvest area would be recalculated after 20 years, resulting in a decline to 2,377 ha per five-year period. This reflects the area temporarily residing out of the area base because of the regeneration delay.

A Age Class Structures over Time



B Harvest Level and Operable Growing Stock Volume over Time (million m3)



Note: Harvest Volume is a five year total

FIGURE 11. Progression of age-class structure, growing stock and harvest volume over the 100-year simulation period with no harvest in Example One.

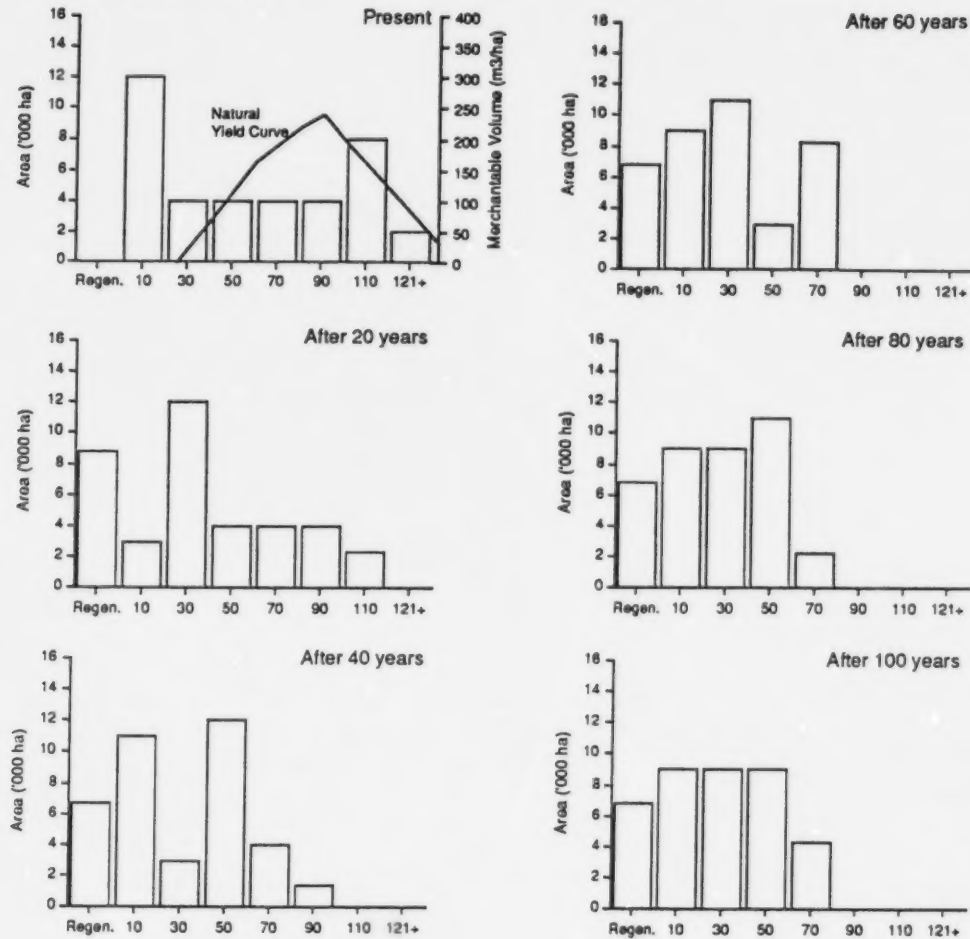
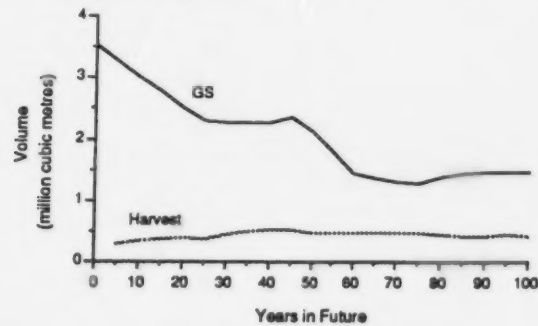
Under the area-regulation scenario, the forest becomes regulated at the end of the simulation period but the path to regulation is not smooth (Figure 12). The growing stock, as expected, declines in this case before levelling off at a regulated level, and the harvest volume fluctuates between 48,360 and 110,400 m³/yr, and this is a relatively flat age-class structure!

If a harvest is proposed under volume regulation, what could be the maximum level without silviculture? After several FORMAN runs, a sustainable level of 97,000 m³/yr of pulpwood was found to be the maximum (see Figure 13) without silvicultural input. What prevents the forest from supporting a yield of 110,000 m³/yr? Running the no silviculture simulation allows the forester to determine the nature of the management problem, based on the forest's unique dynamics of this forest, that prevents a sustained yield of 110,000 m³/yr. Results of the simulation (Figure 14B) show that the harvest cannot be sustained beyond years 56 in the future.

The solution to the problem could either be planting or pre-commercial thinning in juvenile stands. To reflect implementation of these options, yield curves that produce operable stands by age 40 are built into the simulator.

Several forest-level runs (Table 1) show that both pre-commercial thinning and planting at various levels could provide the 110,000 m³/yr. The key difference is the cost. Pre-commercial thinning can achieve the same fibre objective at \$140,000 per year as compared to planting (2.5 m spacing) which would cost \$211,000 per year. Figures 15 and 16 outline the forest indicators resulting from planting and thinning respectively.

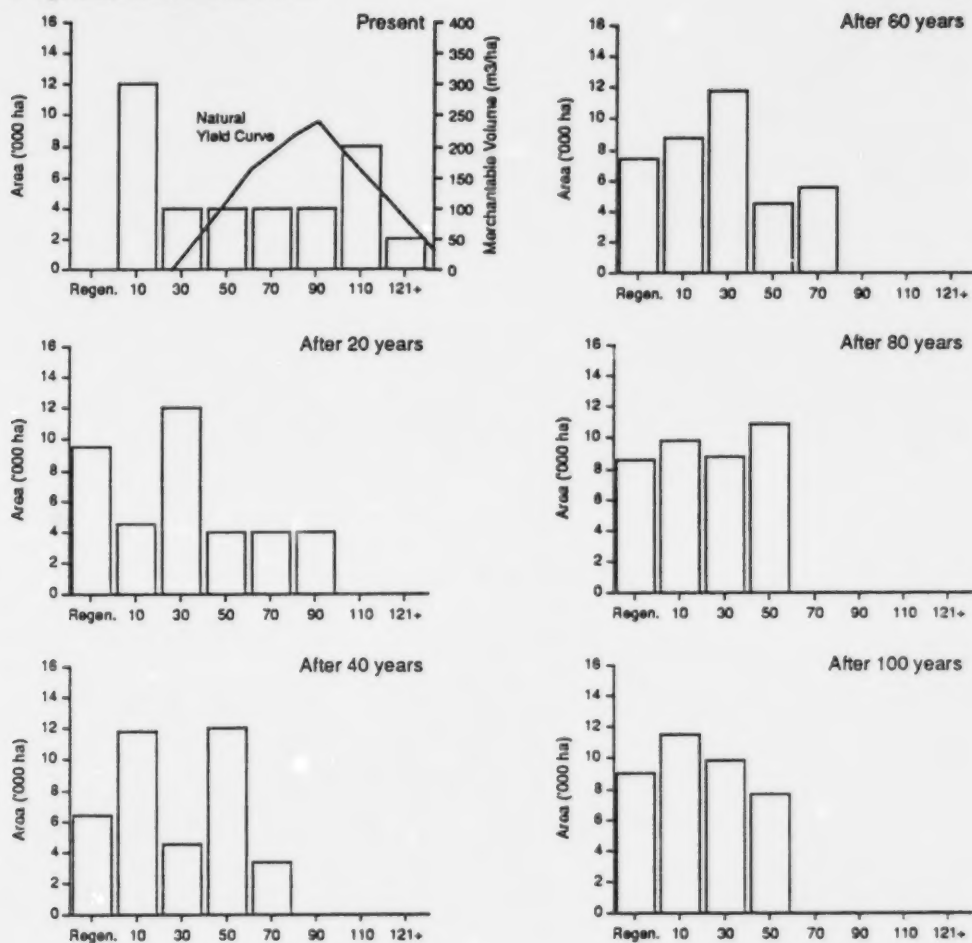
A Age Class Structures over Time

B Harvest Level and Operable Growing Stock Volume over Time (million m³)

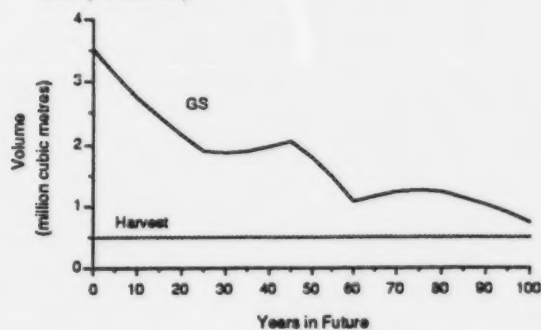
Note: Harvest Volume is a five year total

FIGURE 12. Progression of age-class structure, growing stock and harvest volume over the 100-year simulation period with an area-regulation scenario in Example One.

A Age Class Structures over Time



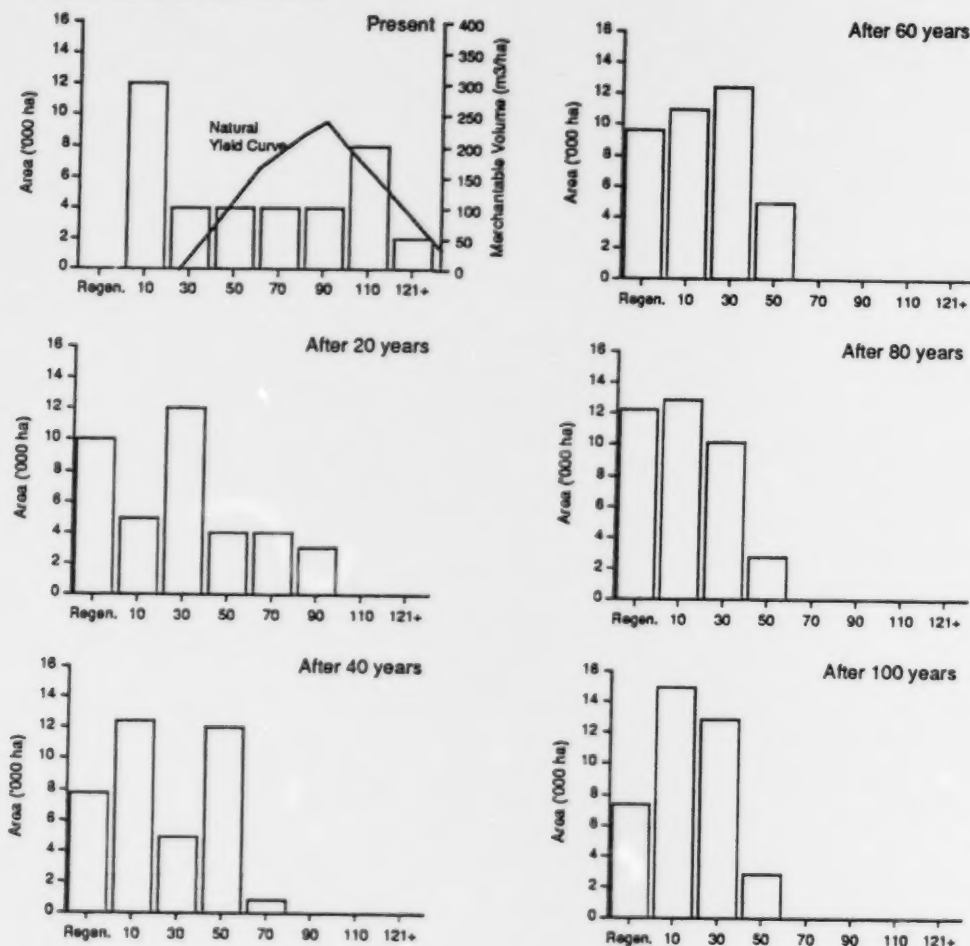
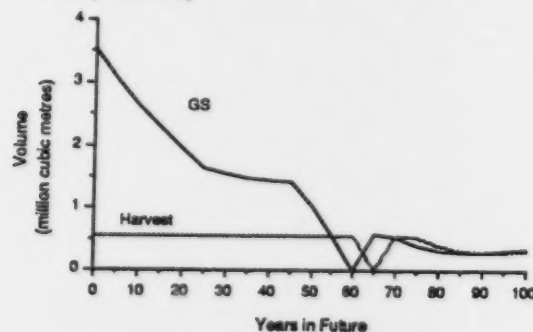
B Harvest Level and Operable Growing Stock Volume over Time (million m3)



Note: Harvest Volume is a five year total

FIGURE 13. Progression of age-class structure, growing stock and harvest volume over the 100-year simulation period with no silvicultural treatment and a harvest level of 97,000 m³/yr. in Example One.

A Age Class Structures over Time

B Harvest Level and Operable Growing Stock Volume over Time (million m³)

Note: Harvest Volume is a five year total

FIGURE 14. Progression of age-class-structure, growing stock and harvest volume over the 100-year simulation period with no silvicultural treatment and a harvest level of 110,000 m³/yr in Example One.

In this example, the most cost-efficient treatment is pre-commercial thinning. Note that for this forest, there are sufficient stands available in which to undertake the required amount of thinning. However, in practice on highly productive sites, natural regeneration, and seeding and thinning, have not been particularly successful. Therefore, for the remainder of the analysis, planting will be used to illustrate the effectiveness of the crop-planning approach. However, the above does illustrate that other successful silvicultural options should be considered on sites where artificial or natural seeding have been successful (e.g. jack pine) - it could save money!

Forest Production Potential

The desired wood supply of 110,000 m³/yr from the forest can be met theoretically by applying a planting or pre-commercial thinning program, or a wide variety of combinations (Table 1, Figures 15 and 16). This yield level could become the forest-management objective, or more ambitious alternatives could be developed.

With planting as the only option for black spruce on Site Class 1A, we found that a maximum harvest of 120,000 m³/yr could be sustained at a cost of \$532,000/yr. This is based on a 2.5 m spacing regime. The sustainable harvest could likely be raised slightly with wider spacings (see Appendix B).

Note that by changing the operability limits from a minimum average diameter of 15 cm to 10 cm, the harvest can be expanded, without additional silvicultural treatment, to 140,000 m³/yr. The lower diameter limit affects the sustainable harvest by decreasing the minimum time before a stand can be available for harvest.

TABLE 1. Combinations of area (and costs) planted and pre-commercially thinned to achieve a sustainable yield of 110,000 m³/yr in Example One.

Area Planted (ha)	Area Thinned (ha)	Annual Cost (M\$)
0	350	140
25	325	153
50	275	157
100	200	174
150	125	191
200	50	208
225	0	211

A Age Class Structures over Time

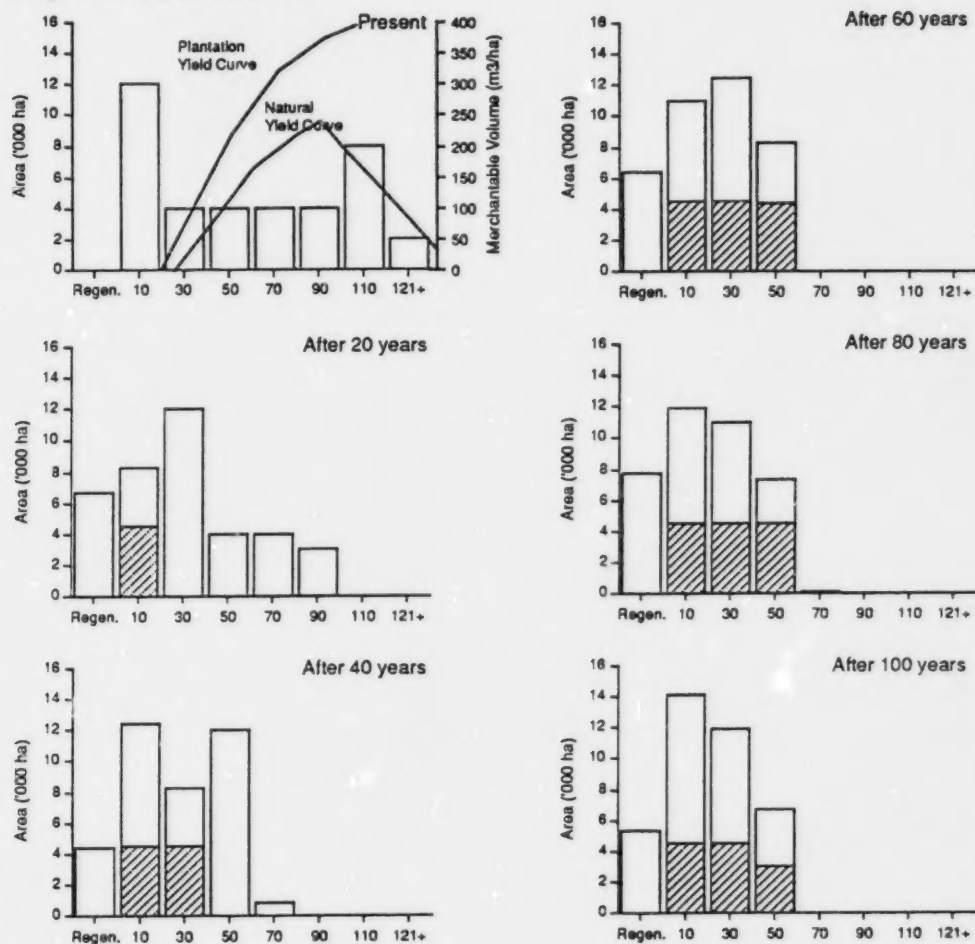
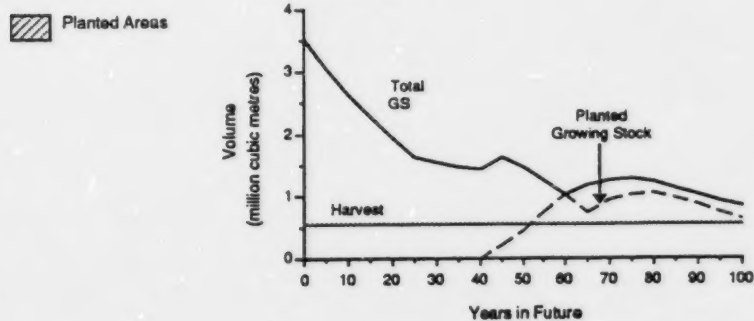
B Harvest Level and Operable Growing Stock Volume over Time (million m³)

FIGURE 15. Progression of age-class structure, growing stock and harvest volume over the 100-year simulation period with planting of 225 ha/yr and a harvest level of 110,000 m³/yr in Example One.

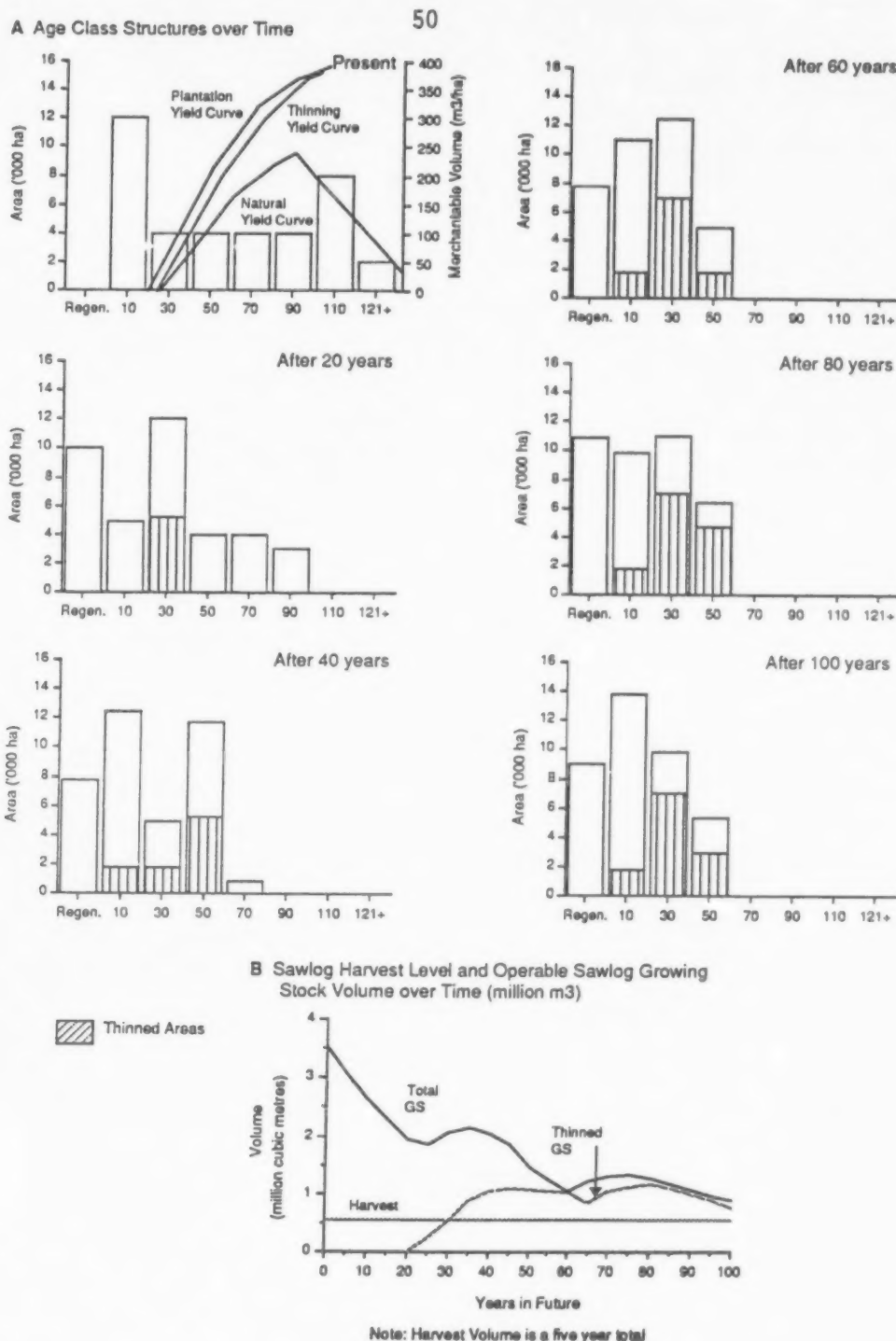


FIGURE 16. Progression of age-class structure, growing stock and harvest volume over the 100-year simulation period with pre-commercial thinning of 350 ha/yr and a harvest level of 110,000 m³/yr in Example One.

This analysis has been limited to tangible silvicultural options (and their associated yield functions). Baskerville (1989a) suggested that further production possibilities could be explored by experimenting with drawn yield curves that may increase the yield even further. For example, what if the natural yield curve in Figure 14 could be raised by 10%? The forest harvest would not crash at year 60-65 but at year 80-90 in the future, thus reducing the effect of pre-commercial thinning while increasing the effect of planting. Overall the sustainable yield would increase. This is a process of exploring the effect of improved (hypothetical) yield functions for a specific forest in trying to enhance production possibilities. The challenge then becomes determining a viable silviculture technique to create the proposed yield (e.g. fertilization of natural stands). The approach requires an excellent knowledge of both forest and stand dynamics.

3.1.3 Forest-Class Analysis - Determination of Silvicultural Ground Rules

The forest-level analysis has defined the forest-management problem (i.e. wood-supply problem in 60-65 years) and several silvicultural strategies that can solve the problem. The forest-class analysis determines the most cost-efficient way to apply the silvicultural options needed to solve the forest-management problem. It could also be used to determine the most cost-efficient way to achieve the yield curve shapes used to solve the forest management problem. The latter assumes that no silvicultural strategy was associated with the yield curve at the time of the forest analysis.

The forest-class analysis for this simple example probably could have been completed during the initial forest analysis. For example, after the initial runs with no treatment, both the yield functions associated with planting and

thinning were likely candidates for increasing the productivity. The most cost-efficient choice could have been inserted instead of a generic silvicultural choice that may not have been the best choice. Recall that the key factor determining cost-efficiency is spacing-regime objective (stand density).

The question can be asked - Is there a real need for the forest-class analysis? The main utility of a forest-class analysis is to save time (i.e. economic analysis tools can evaluate forest classes without the need of full FORMAN runs). A forest-class analysis is always completed during or after the initial forest analysis but it becomes a more distinct step as the forest becomes more complex. It also becomes distinct when not all of the required yield-curve shape changes are identified as silvicultural options in the initial forest analysis.

What is the Most Cost-efficient Treatment?

Four different spacing-regime objectives for the planting option were considered. Economic analysis (see Appendix D) was undertaken to determine the most cost-efficient treatment. Our use of these techniques to evaluate options is on a relative rather than absolute basis. For example, if benefit-cost ratio (BCR) is used, a ratio of 5.57 does not mean that for every dollar invested, 5.57 dollars of provincial wealth are returned. Instead, it means that the relative benefits incurred with a BCR of 5.57 are greater than those with a BCR of, say, two.

The benefit-cost analysis of the four spacing regimes showed that the best BCR occurred at the 2.5 m spacing (Table 2). In absolute terms, the BCR of 5.57 means that \$5.57 of provincial wealth was returned for every dollar invested. However, for purposes of this crop-planning process, the higher BCR simply means

a 2.5 m spacing regime produces relatively higher benefits. Yet, intuitively the higher volumes produced at the tighter spacings (i.e. 1.8 m and 2.0 m) would seem to be the better choice. It appears we are trading volume per hectare for earlier harvestability. Closer-spaced stands produce volume sooner than wider-spaced stands, but the merchantable volume of wider-spaced stands can eventually exceed that of the closer-spaced stands (Appendix B).

Another economic analysis tool used was Present Net Worth (PNW). Also summarized in Table 2 are the results of the PNW analysis completed on the four spacing regimes. This analysis also selected the 2.5 m spacing regime as the treatment that produces the highest relative benefits.

Are there cases when the PNW and BCR analyses will produce different results? For most analyses, both tools will give the same answer. However, as outlined in Appendix D, the PNW tends to give the best answer when budgets are not limited. BCR analysis favours treatments that tend to get the manager closest to solving the forest-management problem when funding is limited.

3.1.4 Final Forest-Level Analysis

The forest-class analysis has determined the most cost-efficient silvicultural ground rules that can produce the desired yield curves needed to solve the forest-management problem. In this example, the forest-class analysis allowed easy evaluation of various spacing-regime objectives which are critical to determining cost-effectiveness. Each spacing-regime objective may have a slightly different yield curve. The final forest analysis involves using final yield curves determined in the forest class analysis to forecast both forest-level costs and economic benefits.

TABLE 2. Maximizing benefit-cost ratio (BCR) and present net worth (PNW) in the forest-class analysis of Example One.

Spacing Regime (m)	Volume at Minimum Age of Availability for Harvest (m ³ /ha)	<u>Benefit Cost Ratio Analysis</u>		<u>Present Net Worth Analysis</u>	
		Benefit/ Cost Ratio	Minimum Age of Availability (yr.)	Present Net Worth (\$/ha)	
1.8	268	4.09	55	4,108	
2.0	231	4.83	50	4,752	
*2.5	162	*5.57	40	*5,423	
3.0	149	5.53	40	5,098	

* Most cost-efficient spacing regime.

Does the Most Cost-Efficient Silvicultural Ground Rule mean the Lowest Cost Solution to the Forest Management Problem?

For illustrative purposes, the four spacing regimes for the planting silvicultural option were evaluated using FORMAN and the yield curves associated with the various densities. The planting programs that would produce a sustainable yield of 110,000 m³/yr were determined (Table 3). The spacing regime of 2.5 m produced the required forest-level sustainable yield at the least cost, and also had the best forest-level BCR and net revenue values (Table 4).

Maximum Production Possibilities

Like cost efficiency, we expected the 2.5 m spacing regime also to produce the maximum sustainable harvest for the forest. However, the 3.0 m spacing regime produced the highest sustainable harvest (125,000 m³/yr - Figure 17) and best forest-level economic efficiencies (Table 5). The slight reduction in volume at operability for the 3.0 m spacing regime was obviously more than offset by the reduced minimum age of availability for harvest. In the forest-class analysis, this was reflected by an almost equal BCRs for the two spacings. We recommend that when the BCRs of options are almost equivalent (i.e., within 5% of each other), one should try them all in the final forest analysis.

The low-cost seed-and-thin option, as expected, also shows the best overall economic efficiencies. However, the maximum yield is slightly lower than with the 3.0 m planting option. This difference is due to the slightly longer growing time required for the seed-and-thin option (see yield curve on Figure 16) due to the 15-year regeneration period.

TABLE 3. Minimum level of planting required by spacing regime at the forest level to maintain sustained yield of 110,000 m³/yr in Example One.

Spacing Regime (m)	Discounted Cost/ha (\$)	At First Operability (m ³ /ha)	Volume Annual Area Planted (ha)	Annual Cost (Discounted) (M\$)
1.8	1174	268	325	382
2.0	1066	231	225	240
*2.5	939	162	225	211
3.0	870	149	250	218

* Best Choice

TABLE 4. Forest-level BCR and PNW values for silvicultural options producing a sustainable yield of 110,000 m³/yr in Example One.

Spacing Regime (m)	**Net Revenue (M\$/yr.)	*Net Annual Revenue Increase (M\$/yr.)	BCR	Annual Area Treated	Annual Cost (M\$)
1.8	16,668	1,633	5.28	325	382
2.0	16,810	1,775	8.40	225	240
2.5	16,839	1,804	9.54	225	211
3.0	16,846	1,798	9.26	250	218
seed/pre-commercial thin	16,691	1,856	12.67	350	159

* value of increased harvest (due to silviculture less cost of treatment)

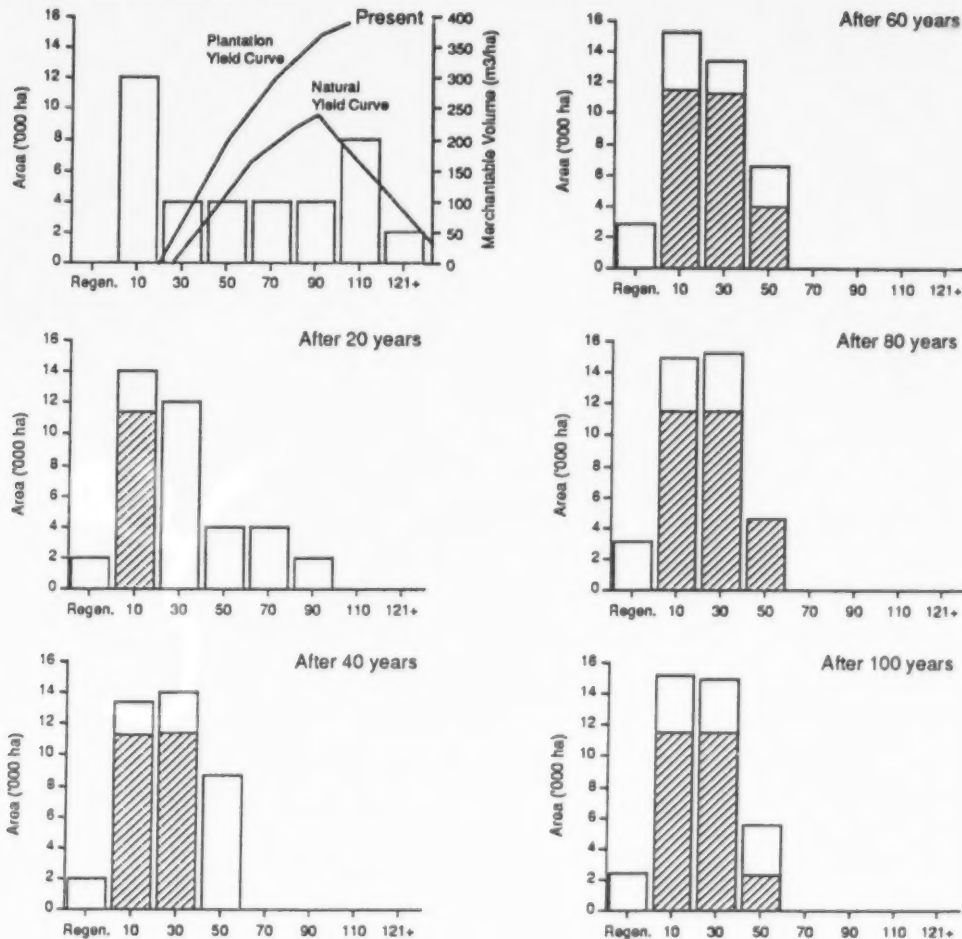
** net revenue is the present-net-worth (PNW) value of the annual sustainable forest harvest.

TABLE 5. Maximum sustainable harvest by spacing regime objective for plantation (and pre-commercial thinning) in Example One (min. 15-cm piece size).

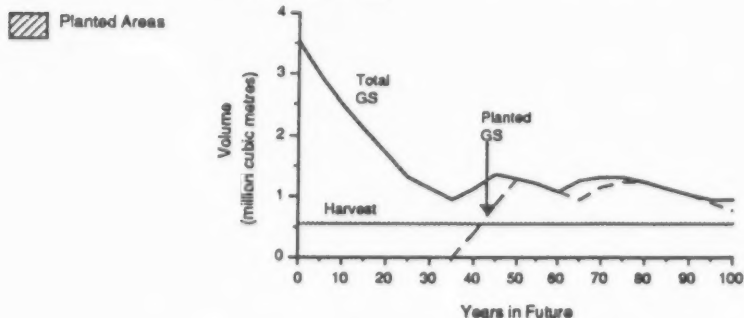
Spacing Regime (m)	Annual Area Planted (thin ratio) (ha)	Annual Cost (M\$)	Sustainable Harvest (M m ³ /yr)	Net Annual Revenue Increase (M\$/yr.)	BCR
1.8	390	458	112	1,867	5.08
2.0	469	480	115	2,775	6.79
2.5	532	437	120	3,283	8.52
*3.0	575	505	125	3,853	8.60
(seed/thin)	695	319	120	3,249	11.18

* = value of increased harvest (due to silviculture less cost of treatment).

A Age Class Structures over Time



B Harvest Level and Operable Growing Stock Volume over Time (million m3)



Note: Harvest Volume is a five year total

FIGURE 17. Progression of age-class structure, growing stock and harvest volume over the 100-year simulation period with a harvest level of 125,000 m^3/yr and planting 575 ha/yr at 3 m spacing in Example One.

Wood Quality and Cost Efficiency

One of the important assumptions we have made in our illustration of the crop-planning process is that wood (fibre) quality remains the same no matter what plantation spacing regime is chosen (Appendix C). This also implies that the value per cubic metre is the same, no matter what spacing regime objective is chosen. Many people dispute this claim. Sawlog companies claim that bigger average piece size developed under a wider spacing regime produces more revenue per cubic metre. Alternatively, some pulpwood companies claim that closer spacing regimes produce higher-value fibre.

To investigate the implications of the claim that narrow spacing produces higher-quality pulp fibre, we completed a forest-class analysis which assumed that there was a 30% premium on each cubic metre of wood produced under a 1.8 m spacing regime. The analysis showed PNW values of 5,338 M\$/yr. and BCR values of 5.32. This is significantly higher than the corresponding 1.8 m values shown in Table 2 but still this regime ranks only third. At the forest-level, this third-place trend continued with a BCR of 9.11 as compared to the other values in Table 4.

3.2 Example Two: A Black Spruce Forest Consisting of One Site Class Producing Sawlogs

3.2.1 Management-Unit Description and Objectives

The same test forest was used for Example Two to allow the reader to contrast the implications of harvesting sawlogs as opposed to harvesting pulpwood. The sawlog component was identified in the yield curves as described in Appendix A.

A forest manager can take two approaches to managing for sawtimber. One would be to manage exclusively for sawlogs and make no effort to influence the production of pulpwood. The manager would simply accept whatever pulpwood volume is cut as a bonus if a market exists. This type of strategy can be dangerous because an uneven flow of secondary products is much harder to sell than a relatively constant flow.

The alternative, probably more appropriate for an integrated firm with a sawmill and a pulp mill, would be to manage jointly for the two products. The forester would explore a range of combinations of product quantities, which may vary in proportion over time depending on the forest dynamics.

The first approach was initially explored by assuming that the forester was required to produce a sustainable annual sawlog harvest of 95,000 m³/yr. Pulpwood production was secondary to achieving the sawlog harvest. An oldest-first harvest rule was followed throughout this case study and a stand was considered to be operable when the average DBH reached 18 cm.

As mentioned above, the sawlog component of the yield curves was isolated (Figure 18) and this resulted in a series of new primary volume curves reflecting only sawlog volumes. This yield curve was used as the basis for selecting the allowable cut and allocating stands for harvest. FORMAN allows an analyst to record the harvest of a secondary product - pulpwood. In this case, the pulpwood yield was obtained by subtracting the sawlog volume yield from the merchantable volume yield curve. The yield curve in Figure 18 assumes small sawlogs based on a log length of 16 feet and only a 4 inch top (see Appendix A, page 105).

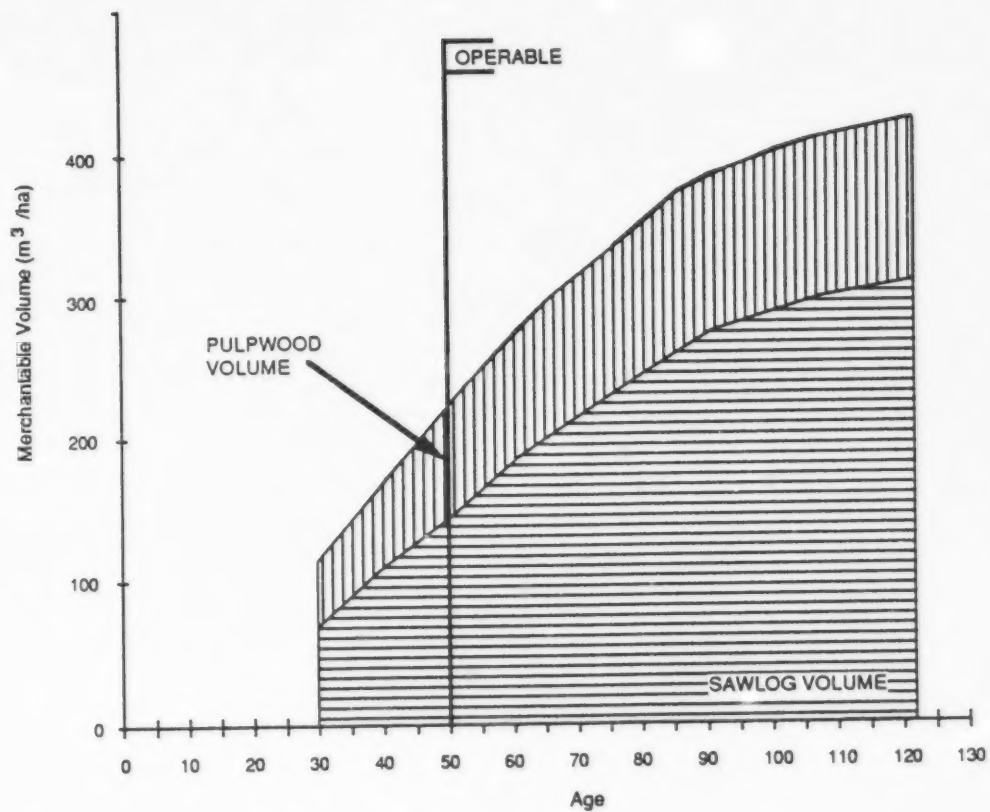


FIGURE 18. Merchantable yields by product for black spruce plantations spaced at 3 m on Site Class 1A in Example Two.

3.2.2 Initial Forest-Level Analysis - Determining the Forest-Management Problem

Could the forest sustain a sawlog harvest of 95,000 m³/yr relying solely on natural regeneration? The answer was no, only 75,000 m³ could be produced in the absence of treatment. The average annual pulpwood yield associated with the sawlog harvest was 4,000 m³.

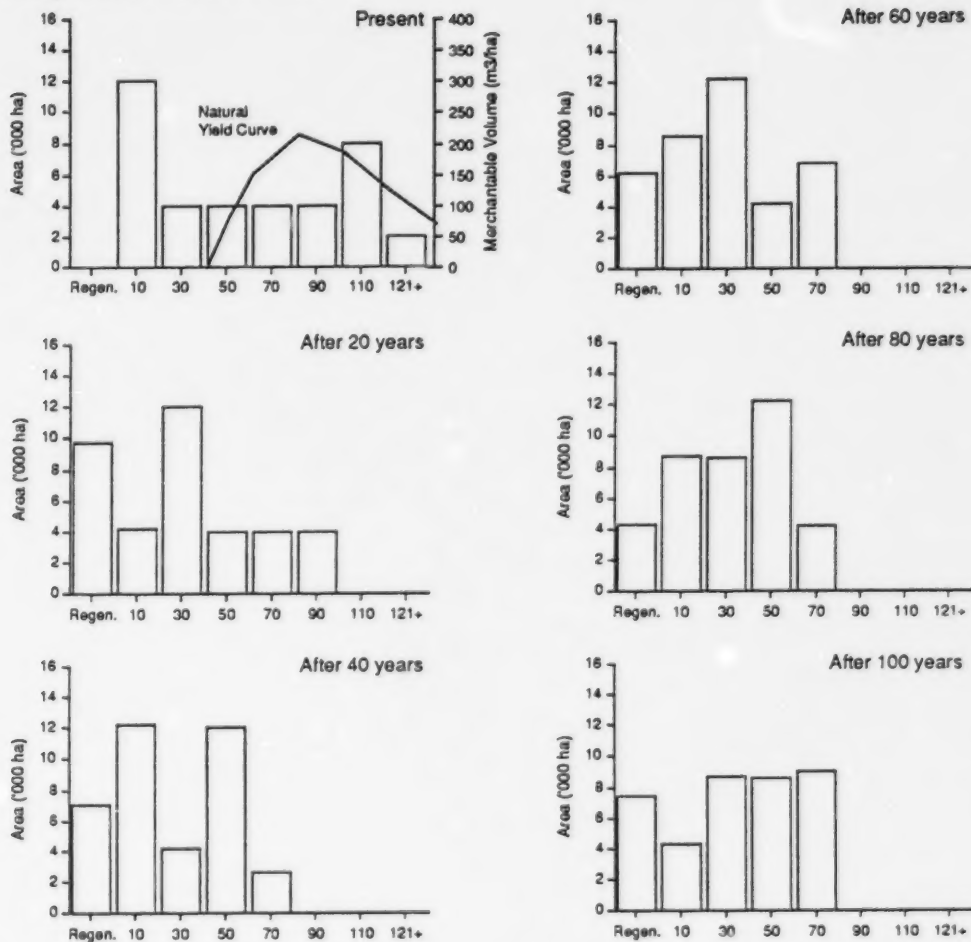
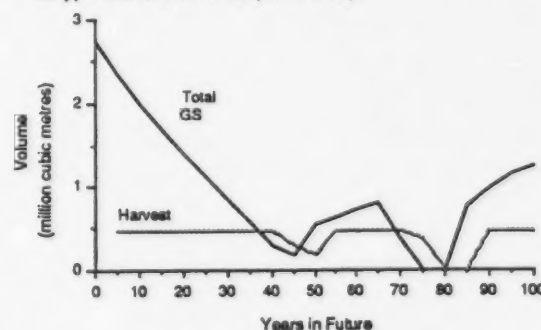
We attempted to take an annual harvest of 95,000 m³. Wood flow was interrupted in years 35-55 (Figure 19). Afterwards, the large initial 1-20-year age class became available and sustained some harvesting for about 40 years. Thereafter, there was not enough sawtimber and the harvest fell to zero. Accordingly, interventions must be designed to increase the sawtimber available from year 35 onwards to meet the target.

What Level of Silviculture Will Solve the Forest-Management Problem?

The forest dynamics outlined in Figure 19 show that the supply problem begins at year 35 when harvesting at the proposed rate of 95,000 m³. Intuitively, planting cannot solve this problem since the first availability for sawlogs is likely 50 to 70 years after planting. Even with unlimited planting, 95,000 m³/yr of sawlogs cannot be sustained (Figure 20). Planting can only help raise the sustainable harvest level to 80,000 m³/yr.

According to Figure 21, the pre-commercial thinning option, following natural regeneration, produces operable stands in a longer time frame than plantations - again, a solution is not apparent. Although not generally considered a viable option for black spruce on Site Class 1A, let us consider it possible for illustrative purposes.

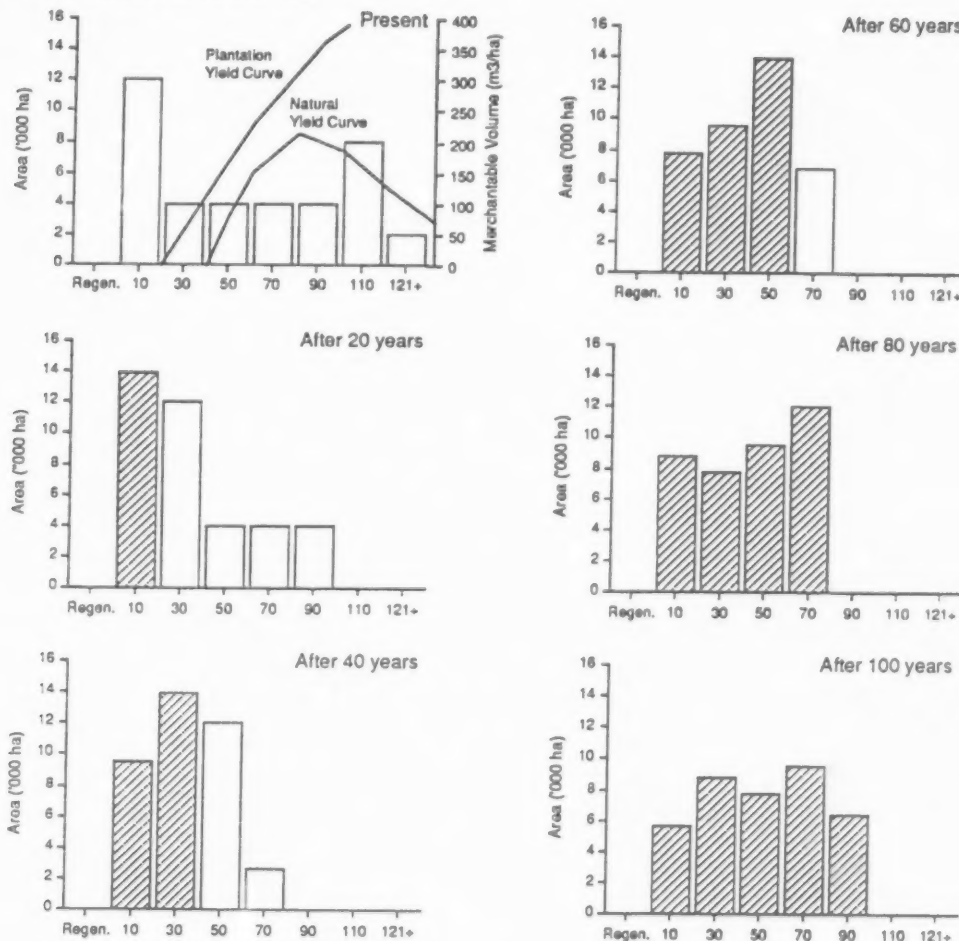
A Age Class Structures over Time

B Harvest Level and Operable Growing Stock (sawlogs only) Volume over Time (million m³)

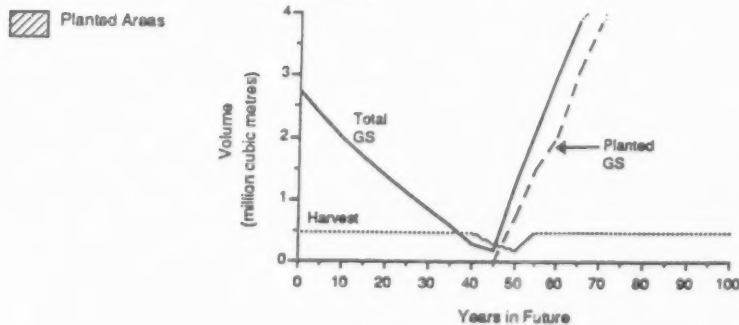
Note: Harvest Volume is a five year total

FIGURE 19. Progression of age-class structure, growing stock and harvest volume over the 100-year simulation period with a sawlog harvest of 95,000 m³/yr in Example Two.

A Age Class Structures over Time



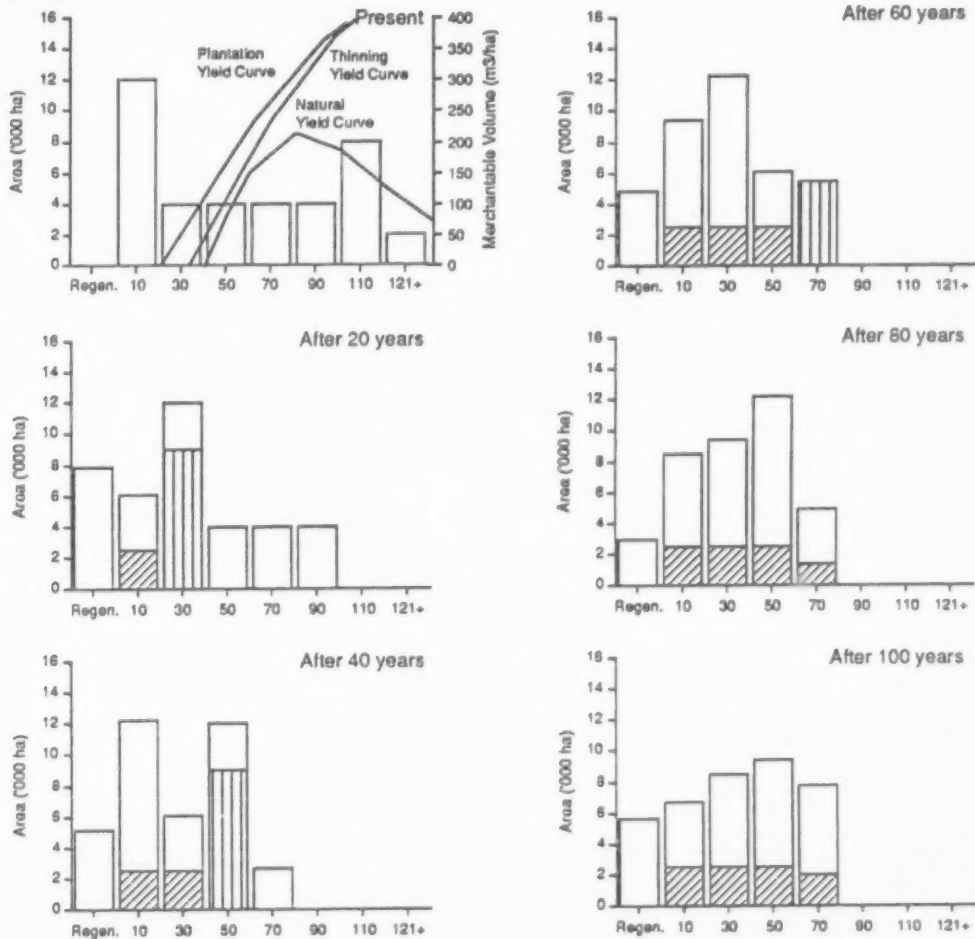
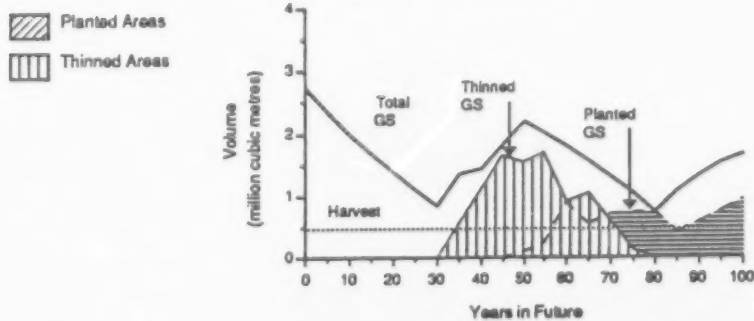
B Harvest Level and Operable Growing Stock Volume over Time (million m3)



Note: Harvest Volume is a five year total

FIGURE 20. Progression of age-class structure, growing stock and harvest volume over the 100-year simulation period with a sawlog harvest of 95,000 m³/yr and full planting in Example Two.

A Age Class Structures over Time

B Sawlog Harvest Level and Operable Sawlog Growing Stock Volume over Time (million m³)

Note: Harvest Volume is a five year total

FIGURE 21. Progression of age-class structure, growing stock and harvest volume over the 100-year simulation period with a sawlog harvest of 95,000 m³/yr, planting 125 ha/yr, and thinning 600 ha/yr in Example Two.

The growth difference between planted and thinned stands (in Figure 21) is caused by the 15-year regeneration delay (assumed) and the slower growth of the naturally regenerated plantation once it is fully stocked. Once thinned, the natural stand is assumed to track along a yield curve with the same rate of growth as that for planted stands at 3.0 m spacing. Costs for thinning are assumed to be \$400/ha.

Figure 21 illustrates that applying both precommercial thinning and planting, where appropriate, allows the sustainable yield to reach 95,000 m³/yr. This can be attributed to the large existing 0-20-year-old age class (15-35 years after disturbance) that can be thinned immediately. By thinning existing stands at age 20, potential operability of the thinned stands will occur 10-15 years earlier than planted stands established at the same time as the thinning. This time reduction for stand operability caused by pre-commercially thinning existing young stands solves the supply problem identified earlier at age 35.

The 15-year regeneration delay assumption made in this example reflect black spruce silvicultural characteristics. For other species such as balsam fir and jack pine on some sites, the pre-commercial thinning option following natural regeneration produces operable stands sooner than plantations (Figure 6b). These species are characterized by speedy natural regeneration resulting in short regeneration delays (e.g. 5 years) and excellent growth response after pre-commercial thinning.

3.2.3 Forest-Class Analysis and Final Forest Analysis

The solution to the supply problem is embodied in the yield curves that apply to 600 hectares of pre-commercial thinning and 125 hectares of planting. What is the most cost-efficient way to apply these strategies? Again, the key to this assessment is spacing-regime objective for both pre-commercial thinning and planting.

A set of benefit-cost values was generated to compare the four spacing regime objectives to recognize that operability occurred at a higher DBH than for pulpwood (Table 6). This analysis should be viewed with some caution because the benefit-cost analysis was conducted so that the benefits from sawlogs and pulpwood were both included and so both influence the PNW and BCR statistics. However, the forest-management objective is dependent only on sustaining sawlog yields. One way around this is to re-calculate the benefit-cost assessment with a value of zero assigned to the pulpwood.

The 3 m spacing regime for planting returned both the best PNW and the best BCR, so there is no doubt that this establishment objective is the most promising (Table 6). In all cases, the best PNW and BCR values occurred at the earliest minimum age of availability for harvest. Minimum operability ages associated with sawlogs are higher than pulpwood (as in Example One). This poses a problem because planting will not contribute any additional wood by year 45. The forest-level analysis shows that planting alone cannot solve the wood-supply problem.

Contrary to planting, the best PNW and BCR for pre-commercial thinning occurred at the narrowest spacing analyzed (2.0 m) (Table 7). This reflects the realistic assumption that the costs for thinning to 2.0 m between trees are lower (by 10%) than a 2.5 m spacing and 20% lower than a 3.0 m spacing. It simply costs more to remove a greater number of trees.

TABLE 6. Most cost-efficient spacing regimes and harvest ages for planting in Example Two.

Spacing Regime	<u>Present Net Worth</u>		<u>Benefit-Cost Ratio</u>	
	Max PNW (\$/ha)	Age ¹ (yr.)	Max BCR	Age ¹ (yr.)
1.8	1,140	75	1.92	75
2.0	1,672	70	2.47	70
2.5	2,354	60	3.45	60
*3.0	3,092	50	*4.05	50
Natural	838	65	na	na

* Best Choice

¹ Minimum age of availability for harvest.

TABLE 7. Most cost-efficient spacing regimes and minimum age of availability for harvest for pre-commercial thinning option in Example Two.

Spacing Regime (m)	<u>Present Net Worth</u>		<u>Benefit/Cost Ratio</u>	
	Max PNW (\$/ha)	Age ¹	Max BCR	Age ¹
*2.0	3,117	50	*7.73	55
2.5	2,848	50	6.97	55
3.0	2,536	55	6.22	55

* Best Choice

¹ Minimum age of availability for harvest.

Does the relative benefit-cost analysis for the forest classes result in spacing-regime objectives which yield the lowest costs and greatest benefits at the forest level? Our results (Table 8) show that a 3.0 m spacing regime for planting and 2.0 m thinning regime provides the most cost-efficient means to solve the forest-level supply problem.

If relative benefit-cost analysis based on a stand-level economic-analysis technique gives the right answer at the forest level, why bother with a forest analysis? The answer is: (a) the forest-level analysis was required to uncover what the forest-management problem actually is (and thus, what type and level of silviculture is needed to solve the problem); and (b) the forest analysis determines only the nature of the silvicultural strategy that can solve the forest-management problem and the forest-class silvicultural options that need to be evaluated.

3.2.4 Forest-Level Economic Analysis

The forest-wide economic analysis is a little more difficult in the sawlog case because of the fluctuating level of pulpwood and sawlogs harvested, but the general idea is the same. FORMAN identifies the volume of primary product (sawlog) and secondary product (pulpwood). Based on the assumptions in Appendix A, the value of lumber works out to \$95/m³. The volume of chips is unknown and must be estimated. The volume of pulpwood varies by an order of four throughout the simulation; its value is \$155/m³, as before. The volume of chips produced from the sawlogs has to be estimated from the average tree size at harvest

TABLE 8. Minimum annual planting and pre-commercial thinning cost to sustain sawlog yield of 95,000 m³/yr at selected spacing regimes in Example Two.

Spacing Regime Objective (m)	Planting Cost/ha (\$)	Annual Area Planted (ha)	*Annual Cost (M\$)
1.8	1,174	impossible	na
2.0	1,066	250	291
2.5	939	150	165
+3.0	870	125	133

* Includes 600 ha/yr. of thinning for each.

+ Best Choice

and the proportion of lumber and chips produced. Here, most of the harvesting is done in 65-85 year old stands where roughly 35% of the log is converted to chips. Therefore, the average chip volume is $0.35 \times 95,000 = 33,250 \text{ m}^3$. The value of a cubic metre of pulp chips was estimated at \$165. The volume of wood valued at \$95/m³ is 65% of 95,000 m³.

The general pattern of harvest is that roughly 14,000 m³ of secondary product are cut in the first three 5-year periods, when all of the pre-commercial thinning is completed. Thereafter, the average 5-year quantity of pulpwood was approximately 32,200 m³. Therefore, the net revenues and BCR's were calculated for an average year in the first 15 years and then for an average year in the last 85 years (Table 9). This was done for three options: planting and spacing to 3.0 m, to 2.5 m, and to 2.0 m. A spacing of 1.8 m is too close to enable the required cut to be taken.

In this case, the 3.0 m option is most favourable throughout the 100-year period according to both criteria. The high total BCR's over the last 85 years of the simulation arise (Table 9) because the benefits from the earlier thinnings are being received but no more thinning (costs) are required (i.e., thinning only occurs for the first 15 years).

3.2.5 Alternative Sawlog Analysis - Integrated Sawlog-Pulpwood

FORMAN permits the forester to simulate an integrated approach to sawlog-pulpwood management. Instead of using a separate sawlog-only yield curve, the user can describe how the percentage of total yield devoted to one product changes over time and FORMAN keeps track of the quantity of this product harvested over time. Unfortunately, with this approach the forester has no direct control over the volume of sawlogs produced. Because the harvest level

TABLE 9. Forest-level economic analysis results in Example Two, where harvest is 95,000 m³/yr.

Option	<u>First 15 Years</u>		<u>Last 85 Years</u>	
	Net Revenue (M\$/yr.)	BCR	Net Revenue (M\$/yr.)	BCR
Plant, Thin 3.0 m	2,657	6.96	2,582	23.74
Plant, Thin 2.5 m	2,626	6.35	2,550	18.10
Plant, Thin 2.0 m	2,200	4.08	2,424	9.09

is linked to the total merchantable yield, the FORMAN user must accept the proportion of sawlogs that happens to be harvested. Then one must decide whether the degree of flux in sawlog flow is narrow enough to be acceptable. This decision will likely hinge on the quantity of sawlogs produced over the first 10-20 years of the simulation, on the opportunities for trading wood, and on the feasibility of separating sawlogs from pulpwood in harvest and transportation operations.

This integrated approach generates product flows that are substantially different from those that arise when a sawlogs-only yield function is used. In essence, the FORMAN runs are the same as those conducted in the previous pulpwood analysis (i.e., Example One), except that now the volume of sawtimber is accounted separately. The total merchantable volume function (i.e., sawlogs plus pulpwood) was retained as the primary volume function in FORMAN and the percentage of the yield at each age that could be used as sawlog material was calculated. The percentages were incorporated into the yield function file, as described in Wang et al. (1987). The operability limits used in this variation were set at an average DBH of 15.0 cm.

When FORMAN was used to evaluate the need for silviculture, the maximum overall annual harvest that could be sustained with no treatment was 97,000 m³ (see section 3.1.2). The average annual yield of sawlog volume was 92,000 m³, with a range of 86,000 m³ to 95,000 m³/yr.

One might think that the difference between the annual sawlog production levels is due to the different operability limits. In other words, would the use of a sawlog-only yield curve have produced an even annual flow of 92,000 m³ if the operability had been lowered from 18.0 cm to 15.0 cm? The answer is no -

the highest even flow that could be achieved was 85,000 m³. The difference, some 7,000 m³ per year, is the cost of the even flow constraint.

What is the Maximum Yield of Pulpwood and Sawlogs?

The integrated sawlog-pulpwood approach is probably the most realistic and also provides more flexibility to answer the question: what is the highest combined average annual sawlog and pulpwood sustainable yields? The answer is 125,000 m³/yr (Table 10).

As in the sawlogs-only option, the 3.0 m spacing regime proved to yield the greatest total volume, the greatest average annual volume of both products and at the lowest cost and with the greatest benefits.

3.3 Example Three: A Black Spruce Forest With Three Site Classes Producing Pulpwood

3.3.1 Management-Unit Description

While the examples above are useful for identifying the process and the main considerations used to devise crop strategies for achieving forest-level goals, their simplicity masks the real analytical utility of the crop-planning process.

Consider a spruce forest from a typical North Central Region management unit of 197,796 ha (e.g., Thunder Bay District); it consists of 36,563 ha in Site Class 1A, 109,689 ha in Site Class 1, and 51,544 ha in Site Class 2. The age-class distributions again show a preponderance of mature and overmature stands (Figure 22A and 22B). Similar operability and regeneration-delay assumptions as in Example One were applied in this example.

TABLE 10. Maximum sawlog and pulpwood yield with associated costs and benefits for selected plantation spacing regimes in Example Two (integrated sawlog-pulpwood version).

Spacing Regime Objective (m)	Average Sawlog Volume (M m ³ /yr)	Average Pulpwood Yield (M m ³ /yr)	Average Annual Cost (M\$)	Average Annual 20-year Cost (M\$)	Net Revenue Increase (M\$)	BCR
1.8	101	9	606	880	1,075	1.77
2.0	105	10	581	820	1,733	2.98
2.5	109	11	549	735	2,398	4.37
*3.0	113	12	573	698	3,007	5.25

* Best Choice

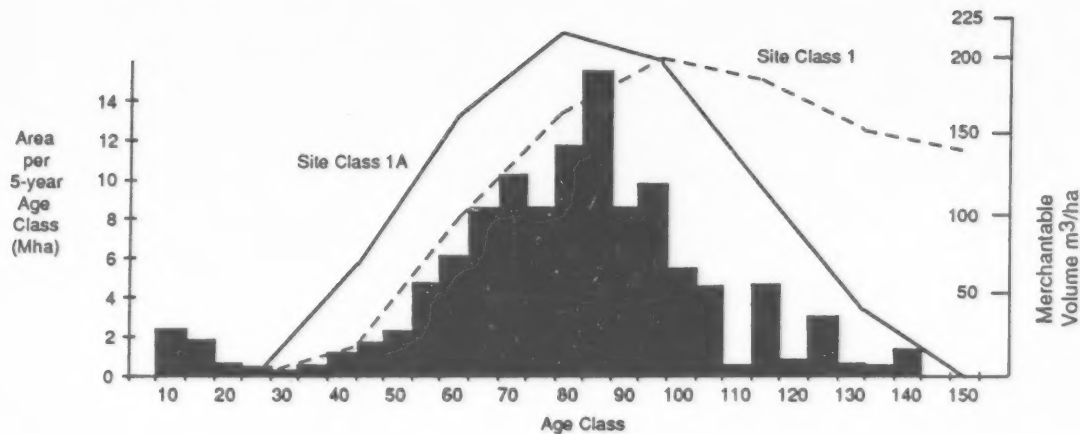


FIGURE 22A. Age-class structure and natural yield curve of the Site-Class-1 black-spruce component of the forest in Example Three.

* The age-class structure of Site Class 1a is proportional to that for Site Class 1, actual areas being 1/3 as large as in Site Class 1.

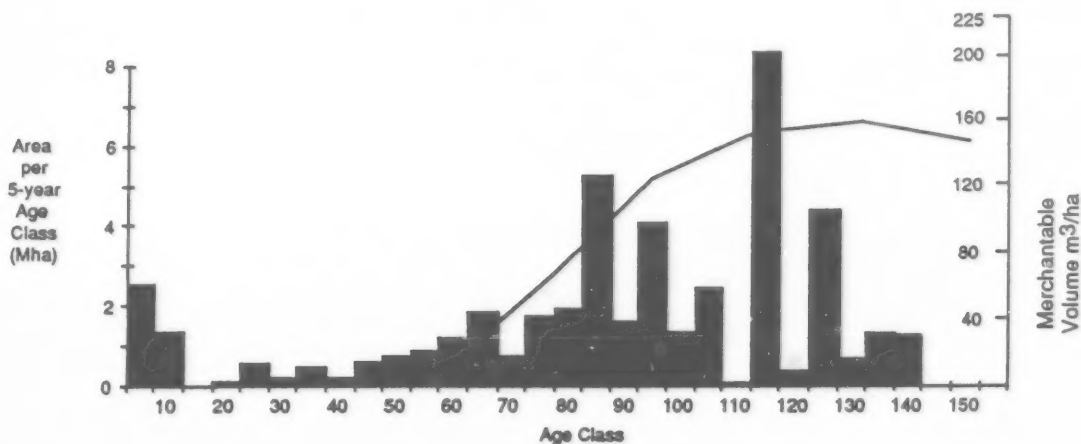


FIGURE 22B. Age-class structure and natural yield curve of the Site-Class-2 black-spruce component of the forest in Example Three.

It is interesting to compare among the various natural and variable-density tables how the 15 cm operability constraint influences the minimum harvest age. Not surprisingly, this minimum timing of availability for harvest varies by site class as well as spacing regime (Table 11).

The presence of more than one site class adds additional dimensions to the analysis, making the example more realistic but still tractable. The manager must prioritize areas for planting on the basis of site. In this example (although not always appropriate in every case), Site Class 1A was given highest priority followed by Site Class 1 and 2 respectively. The increased complexity of the forest dynamics increases the importance of harvest rules as an important part of the crop-planning process. The proposed management-unit objective here is to provide a sustained yield of 500,000 m³/yr. Again, the forester is asked to provide this level of yield in the most cost-efficient manner.

3.3.2 Initial Forest-Level Analysis - Determining the Forest-Management Problem

The first question is: what is the sustainable harvest level without any silviculture? Also, the harvest rule of "oldest first" becomes important now that there are stands tracking different yield curves and different minimum harvest ages. An additional important question is: does the oldest-first rule affect the sustainable harvest level, and if so, how? With the oldest-first rule in place, the sustainable yield without silviculture is 280,000 m³/yr. Application of the minimum-volume-loss harvest rule raises the sustainable yield to 375,000 m³/yr. This rule directs cutting to stands that are losing volume fastest, i.e., on the steepest portion of the declining side of any of the applicable yield curves. It also allows some old stands to just grow old and

TABLE 11. Merchantable yields at minimum age of availability for harvest with a 15-cm operability limit in Example Three.

Spacing Regime (m)	Minimum Age of Availability for Harvest			Volume (m ³ /ha)		
	X	Site Class 1	2	X	Site Class 1	2
Natural	50	90	110	116	200	170
1.8	55	75	110	268	254	250
2.0	50	70	95	236	237	236
2.5	40	55	80	162	157	169
3.0	35	45	65	119	102	116

breakup. Thus, in this case the oldest-first harvest rule directs the harvest to stands which have already lost large volumes due to overmaturity, while somewhat younger (but still overmature) stands are in the process of losing significant quantities of timber (Willcocks 1977).

We applied another harvest rule, that of maximizing harvested volume per hectare, and found a maximum sustained yield (with no silvicultural treatment) of 305,000 m³/yr. This rule, applied to this forest, lowers the unit harvest costs/ha but at a lower sustainable yield. Again, the harvest rule of maximizing harvested volume per hectare lets old, declining stands in the forest remain unharvested. These stands break up and regenerate naturally.

We turn to the yield curves and the age-class structures (Figure 22) for an explanation for the lower sustainable harvest when implementing the harvest rule of maximizing harvested volume per hectare, compared with the harvest using a rule of minimizing volume losses. A significant area of Site Class 1a and 1 is in the 70-110-year age classes. These stands are nearing their peak volume/ha and leaving them would result in the loss of approximately 50% of their volume over the next 20 years. However, this forest has a significant area of older, decadent stands with much lower volumes per hectare. Thus, in this particular forest, use of the oldest-first rule allocates stands that have already begun to collapse, meanwhile allowing younger, higher-volume stands to begin to collapse. The oldest-first rule perpetuates an inefficient harvest allocation. The important point, as stressed by Baskerville (1986), is that the blanket application of one harvest rule for all forests fails to recognize the influence of a forest's characteristics such as age-class structure on sustainable yield.

In FORMAN, there are seven harvest rules to choose from. In this case, the rule of minimizing volume loss was more appropriate than the oldest-first rule.

Silvicultural input will be required to achieve an annual harvest of 500,000 m³/yr. By running FORMAN with this harvest level, the harvest could be obtained for the first 65 years only using the oldest-first rule, and for 75 years with the minimizing-volume-loss rule. Planting was indicated as the solution to the wood-supply problem. Pre-commercial thinning was not considered a viable option here because artificial or natural seeding are not generally successful on black spruce Site Class 1 and 1A land in Northern Ontario. After a number of FORMAN runs, a planting program of 1,350 ha/yr was found to permit a sustainable yield of 500,000 m³/yr.

3.3.3 Forest-Class and Final Forest Analysis

The utility of completing a benefit-cost analysis on forest classes after the initial forest-level analysis, became apparent in this complex example. With three forest classes representing treated stands (as well as three classes for natural stands) and four spacing regimes to be assessed, there are significant time savings in undertaking forest-class analysis. As expected, the best choice for each forest class (i.e. site class) selected by PNW and BCR are identical (Table 12). A 2.5 m spacing regime is best on Site Class 1A and a 3.0 m regime is best on the other two forest classes (Table 12). The wider spacing regime of stands on site classes of lower productivity partly offsets the time it normally takes these stands to reach operability.

TABLE 12. Summary of forest-class economic indicators and minimum available age for harvest by plantation spacing regime in Example Three.

Spacing	<u>Present Net Worth</u>		<u>Benefit-Cost Ratio</u>	
	PNW	Age ¹	BCR	Age ¹
<u>Site Class 1A</u>				
1.8	4,108	55	4.09	55
2.0	4,752	50	4.83	50
*2.5	5,423	40	*5.57	40
3.0	5,098	35	5.53	40
<u>Site Class 1</u>				
1.8	956	75	1.77	75
2.0	1,383	70	2.21	70
2.5	2,122	55	3.00	55
*3.0	2,218	45	*3.11	45
<u>Site Class 2</u>				
1.8	-662	110	0.44	110
2.0	-235	95	0.79	95
2.5	207	80	1.21	80
*3.0	581	65	*1.62	65

* "Best" choice

¹ Minimum age of availability for harvest.

Do the Most Cost-efficient Treatment Choices at the Forest-Class Level Produce the Least Costs and Most Benefits at the Forest Level?

To verify the economic results of the forest-class analysis, all combinations of spacing regimes were implemented in a final forest-level analysis. It was found that the sustainable harvest level of 500,000 m³/yr could be generated with many variations of spacing-regime objectives over a wide range of costs (Table 13). Depending on how one measures costs and benefits, the best strategy determined in the forest-class analysis is either that with the lowest or second lowest cost, or that which returns the highest or second highest benefits while sustaining the desired volume. Thus, in this case the forest-class analysis gave a reasonable approximation of the management strategy that was economically superior in the forest-level analysis.

A number of observations concerning establishment strategy can be made here. First, there are several regimes that are roughly equivalent in terms of cost and sustained harvest level (Table 13). This provides the manager with some flexibility to achieve other secondary objectives which may not have been incorporated into the analysis. Second, options where Site Class 1 plantations are established at 2.0 m density consistently under-perform. For example, the additional 15-30 year wait for operable wood that ensues if 2.0 m spacing is adopted, as compared to wider spacing regimes, forces the harvest into the youngest stands on all site classes and the harvest cannot be sustained. However, if the plantations on Site Class 1 become operable earlier (i.e. as a result of wider spacing), the harvest can be sustained with less planting effort.

TABLE 13. Costs and treated area by crop production strategy to ensure sustainable yield of 500,000 m³/yr in Example Three.

Spacing Combination Site Class			Minimum Planting Level (ha/yr)	Total Cost (MM \$)	20-Year Cost (M \$)	Forest Level BCR
X	1	2				
3.0	3.0	3.0	1300	106	+21.8	12.77
	2.5		1350	110	24.1	12.54
	2.0		1750	169	33.3	10.37
3.0	3.0	2.5	1300	110	22.6	12.58
	2.5		1350	119	24.1	12.46
	2.0		1750	168	33.3	10.27
3.0	3.0	2.0	1300	111	22.6	12.02
	2.5		1350	120	24.1	11.92
	2.0		1750	171	33.3	10.05
*2.5	3.0	3.0	1200	105	22.1	13.66
	2.5		1300	118	24.4	12.68
	2.0		1650	162	32.7	10.89
2.5	3.0	2.5	1200	105	+22.1	12.73
	2.5		1350	123	25.4	12.48
	2.0		1700	168	33.7	10.61
2.5	3.0	2.0	1200	106	+22.1	12.30
	2.5		1300	119	24.4	12.04
	2.0		1650	164	32.7	10.23
2.0	3.0	3.0	1200	115	24.3	12.62
	2.5		1250	120	25.7	12.81
	2.0		1650	169	35.2	10.65
2.0	3.0	2.5	1200	112	24.3	12.41
	2.5		1250	121	25.7	12.60
	2.0		1650	170	35.2	10.54
2.0	3.0	3.0	1200	112	24.3	11.99
	2.5		1250	121	25.7	12.20
	2.0		1650	171	35.2	9.96

* Best choice on an individual forest class basis (from Table 12).

+ Other better or comparable choices when Site Classes are combined.

The particular outcome of this case depends heavily on the age-class structures of the forest classes, the yield curves, and the harvest level. Because the choice of the preferred silvicultural strategy depends on situation-specific factors, forest managers must be able to undertake and understand their own analyses.

What are the Maximum Production Possibilities?

Further forest-level simulations indicate that the forest can sustain a harvest of 610,000 m³/yr using the "best choice" silvicultural option (planting) outlined in Table 13 (i.e., planting at 2.5 m for Site Class 1A, 3.0 m for Site Class 1, and 3.0 m for Site Class 2). Results of applying all the forest-level options outlined in Table 13 are given in Table 14. The option providing 610,000 m³/yr using the "best choice" silvicultural options has the highest forest-level BCR, but not the highest sustainable harvest (i.e., 620,000 m³/yr). This shows that in some cases, higher volumes can be generated but at lower rates of return.

Influence of Harvest Rule on Forest-Level Sustainable Yield

Previously, we chose the minimum-volume-loss harvest rule because of the forest dynamics (i.e. preponderance of overmature and mature stands that are susceptible to significant volume loss). Was it the right choice? For maintaining sustainable yield of 500,000 m³/yr, the minimum-volume-loss harvest rule performed the best (Table 15). The same harvest rule produced the highest possible sustainable yield and again at the lowest cost.

TABLE 14. Costs, benefits, and maximum harvest by plantation spacing regime in Example Three.

X	Spacing Site Class	2	Maximum Harvest Level (M m ³ /yr)	Unit Cost (\$/m ³)	Forest Level BCR
3.0	3.0	3.0	600	4.55	18.28
	2.5		605	4.70	17.61
	2.0		545	4.66	11.46
3.0	3.0	2.5	600	4.62	17.61
	2.5		605	4.73	16.28
	2.0		545	4.71	11.53
3.0	3.0	2.0	590	4.70	17.45
	2.5		590	4.74	16.15
	2.0		545	4.81	11.33
2.5	3.0	3.0	610	*4.62	18.45
	2.5		610	4.71	16.42
	2.0		560	4.70	11.96
2.5	3.0	2.5	605	4.63	18.45
	2.5		605	4.72	16.28
	2.0		555	4.74	11.53
2.5	3.0	2.0	595	4.66	18.28
	2.5		595	4.76	16.28
	2.0		550	4.82	11.81
2.0	3.0	3.0	610	4.73	16.85
	2.5		620	4.78	16.15
	2.0		560	4.81	11.46
2.0	3.0	2.5	605	4.75	17.30
	2.5		615	4.80	16.01
	2.0		560	4.86	11.40
2.0	3.0	3.0	595	4.78	17.30
	2.5		605	4.83	16.01
	2.0		550	4.95	11.33

* Recommended Option

TABLE 15. Forest-level costs and benefits for a harvest of 500,000 m³/yr and maximum sustained yield based on selected harvest rule in Example Three¹.

Harvest Rule	Planting (ha/yr)	Annual Cost (M\$)	Net Revenue Increase (M\$)	BCR
A) <u>For 500,000 m³/yr</u>				
Oldest first	1,900	1,600	17,746	11.89
Minimum Volume Loss	1,200	1,050	18,325	18.45
B) <u>Maximum Sustainable Volume</u>				
Oldest First (595,000 m ³ /yr maximum)	3,470	3,240	31,201	11.76
Minimum Volume Loss (610,000 m ³ /yr maximum)	3,150		35,309	14.25

¹ Based on planting 2.5 m for Site Class X, 3.0 m for Site Class 1 and 2.

4.0 CONCLUSIONS

4.1 Development of and Need for a Crop-Planning Process

The link between forest-level planning and stand-level implementation in Ontario has been weak. User-friendly forest-resource simulators such as FORMAN provide an opportunity to improve forest-level planning by substantially increasing the forester's analytical capability by quickly adapting forest-level management changes to realities at the stand level.

Key to the crop-planning process is determining the management problems and objectives of a particular forest in a manner consistent with the dynamic structure of the specific forest. Solutions to the defined problems are based on harvest and silvicultural strategies applied to the unique dynamics of the forest. These activities are planned at the forest level but applied at the stand level. The bridge between the stand and forest is the forest class (or treatment unit, or stand type) which is a homogeneous collection of similarly growing stands. There could be dozens of these stand types or "small forests within a forest" in any one forest-management unit. Strategies, or ground rules, applied to these types guide actual field implementation at the stand level. The accuracy of a crop plan is dependent on how (a) consistently the strategies are applied at the stand level, (b) accurately the forest classes are defined, and (c) accurately growth is projected for each forest class.

4.1.1 Understanding Forest and Stand Dynamics

Stand-level growth drives the dynamics of the forest. Growth in each of the thousands of stands in a forest contribute to overall forest development. When the stands are lumped into forest classes, the forest dynamics are driven by the class yield functions.

Since forest-level problems relate to the performance of component stands, changing the yield functions for particular stand types is the route to solving forest-level problems. Yield curves are changed in reality by silvicultural treatment. The challenge is finding the right harvest schedule and treatment regime that will solve the problem. Complicating this is the perception that accurate, tested stand-yield curves do not exist. This report questions that perception and challenges foresters to develop their own yield curves based on sound biological knowledge that presently exists. If we wait for curves to be developed from plantation data, it could be too late.

4.2 Economic Analysis Tools

4.2.1 Forest Class

Once the yield curves (or generic silvicultural strategies) are determined, benefit-cost analysis can be used to determine the most cost-efficient silvicultural options or ground rules that can make stand development follow those curves. This is a relative measure of efficiency and not additive when applied to stands in a forest-level context. However, for the example shown here our results indicate that most cost-efficient strategies at the class level generally hold at the forest level as well.

4.2.2 Forest

Applying economic tools at the forest level does not assume the additive response of the separate forest-classes, but rather included examination of how silviculture alters the position of stands in the harvest queue for the forest. The basic assumption is that each level of management input produces a sustainable harvest or allowable cut. More or less input will vary the harvest

level that is sustainable. Therefore, this effect on allowable cut can be manipulated and economically assessed on an annual basis. For this report, such assessments were based on an assumed provincial value-added figure; however, company profits can just as readily be used in such circumstances.

4.3 Stand Density or Spacing-Regime Objective, An Important Variable in Crop Planning

Setting spacing-regime objectives (i.e. the number of well-spaced trees/ha desired at the free-to-grow stage) for stands has been largely ignored in management planning in Ontario. Yet spacing-regime objective affects:

- * minimum time for a stand to be available for harvest (i.e. wider spacing decreases the minimum time for harvest);
- * cost of silviculture;
- * crop tree piece size and wood quality.

The three examples were used to illustrate the cost and benefit advantages of varying spacing regimes.

4.3.1 Stand Monitoring

When a treatment is applied at the stand level, the forester assumes that subsequent growth will track along a specific growth curve associated with the treatment. Feedback through regeneration and growth surveys on stands in the forest class are needed to verify the assumption. If significant differences between forecast and actual growth are found, the supposed solution to the forest-management problem may not work. An effective error- detection mechanism will provide timely course changes in forest-management direction.

4.4 Area Regulation Versus Volume Regulation in Crop Planning

The Ontario Ministry of Natural Resources has mainly used area regulation of timber harvest in forest planning, with occasional use of volume regulation. Reliance on area-based control of harvests from natural and unregulated forests can result in wide fluctuations in annual harvest volumes until the forests are fully regulated. For most forest management units in Northern Ontario, with unbalanced age-class structures dominated by mature and overmature stands, full regulation can only be achieved many decades into the future. Crop planning based on volume regulation can add much insight into the effects of both area and volume regulation of sustainable yields, and can thus be usefully employed in the timber-management planning process.

4.5 Next Steps in Development and Use of the Crop-planning Process

The goal of the Northwestern Ontario Forest Technology Development Unit (NWOFTDU) is to assist field foresters in Northern Ontario in gaining and applying crop-planning skills. The next steps are as follows:

1. Incorporate the crop-planning process into MS-DOS software for use on portable computers.

This task is presently underway.

2. Assist field foresters in understanding and implementing the crop-planning process.

A forester skilled in crop planning is essential to develop the best silvicultural strategies or ground rules for each forest-management unit. The forester has to have a knowledge of the crop-planning process but also a clear understanding of forest and stand dynamics. In addition to wide distribution of this report, the NWOFTDU will be holding workshops to help build the required knowledge and skills once the crop-planning software becomes available.

3. Develop improvements to the crop-planning process.

The process described in this report develops silvicultural strategies to achieve timber or fibre objectives. In future, we will tailor the process to the achievement of wildlife habitat or other resource objectives. The key here is development of the relationships between habitat or other resource values with the vegetation/site patterns within management units.

4. Develop mixedwood yield tables.

Many new forests established in Northern Ontario will be mixedwood, yet at present there are no yield tables that reflect this cover type. First- approximation tables for mixedwood growth are required.

5. Develop yield functions based on biological principles.

Yield functions will be refined based on data and on biological principles. First-approximation tables can be built now based on biological principles instead of waiting for data based on plantation growth.

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APPENDIX A

**Summary of Crop-planning
Analysis Steps and Assumptions**

STEP-BY-STEP ANALYSIS SUMMARY

This section is intended to give an overview of the analytical procedure of the crop-planning process. A detailed outline will be included with the software, which is scheduled for release in early 1990. Also included will be an updated FORMAN user's guide.

Initial Forest Analysis

Objective:

To define the forest-management problem in terms of the unique forest dynamics of the management unit (i.e. what element of forest dynamics prevents achievement of required outputs from the forest?) and define the nature of potential solutions to the defined problem. The steps are:

1. Identify the Forest Classes

All forest stands must be stratified into classes, based on site, age, species, and any other important variables.

2. Input the Forest-Class Data into a FORMAN Forest-Class Computer File

The required format is described in Wang et al. (1987).

3. Set Operability Limits

Determine the earliest a stand can be economically harvested to produce the required products. Piece size (i.e., number of trees per cubic metre), average tree DBH, or any other relevant characteristic may be used to determine operability.

4. Choose or Develop Appropriate Yield Functions

Select both natural- and managed-stand yield tables associated with each forest class to reflect adequately the growing conditions of the unit. Depending on the goals of management, yields of specific products or secondary species may also have to be determined. These data must be entered into a computer file, formatted as described by Wang et al. (1987). The yields must also be used in the forest-class analysis (Step 8).

5. Define The Forest-Management Problem

Using a FORMAN analyses, examine the dynamics of the forest using various management regimes such as:

- no harvest
- harvest at various levels and, using various harvest rules without any silviculture, determine under what conditions the forest achieves maximum sustainability without silviculture.

Can the forest in its present state and under its present managerial regime provide the harvest levels desired?

6. Begin Solution Design

Step 5 will reveal, based on forest dynamics, when wood shortages may occur in the forecast period. What yield-curve shape for each of the forest classes will solve this problem? Are there any silvicultural treatments that are associated with these shapes?

The first step in solution design is selection of the hypothetical or actual silvicultural curves that apparently correct the forest-management problem.

7. Exploring Production Possibilities and Setting a Tentative Wood-Supply Objective

What are the possible sustainable yields using existing and realistic alternative yield curves? Under what silvicultural strategy can the forest sustain a harvest at historical or current levels? Under what silvicultural strategies can the forest sustain higher harvest levels? Choose a tentative wood-supply objective, with its associated silvicultural strategy, to be examined more fully in forest-class analysis.

Forest-Class Analysis

Objective:

To determine the most cost-efficient silviculture treatments to achieve the silviculture strategies determined in the forest analysis. The key to cost-efficiency is spacing-regime objective or stand density.

8. Calculate Silviculture Regime Costs and Benefits

Calculate per-ha costs and benefits for each silvicultural regime under consideration (see Appendix D).

9. Undertake Benefit-Cost Analysis

Perform benefit-cost analysis and determine most cost-efficient silvicultural strategy for each forest class.

Final Forest Analysis

10. Determine Overall Costs (and Benefits) when Using Most Cost-efficient Silvicultural Strategies

The most cost-efficient silvicultural ground rule determined in the forest-class analysis needs testing at the forest level to see if it is the most cost-efficient way to solve the overall forest-management problem when the FORMAN simulator is re-run.

FIELD IMPLEMENTATION, MONITORING AND FEEDBACK

11. Application of Ground Rules to Stands

The silvicultural prescription for each stand is based largely on the strategy for the forest class to which the stand belongs.

12. Monitoring and Feedback

Does application of the strategies result in stands that have growth characteristics similar to those used in the forest analysis? Are the benefits and costs reasonable?

A key component of a monitoring program is the free-to-grow survey which evaluates growth, survival, and natural ingrowth.

Error detection using data from surveys will provide feedback to the crop planner. This will undoubtedly result in adjustments to crop plans, and to the management input needed to meet forest objectives.

ANALYSIS ASSUMPTIONS

Overview

Many of the assumptions used in a crop-planning analysis are unique to the specific management unit to be analyzed. These assumptions are either explicit or implicit in every statement about forest development. Our major assumptions are outlined below.

Forest Analysis

When running the FORMAN forest-level simulator, the following was assumed unless otherwise stated:

- the harvest rule "oldest first" was generally applied;
- 100-year planning horizon;
- growing stock could not go below 150% of sustainable harvest level for any five year period;
- minimum operability of 15 cm mean DBH was used for pulpwood;
- minimum operability of 18 cm mean DBH was used for sawlogs; and
- untreated cutover was regenerated naturally and followed the yield curves for existing natural stands.

Use of Yield Tables

Variable density yield tables (Bell, Willcocks, and Kavanagh 1989) were used for the planted and pre-commercially thinned stands. For the natural stands, empirical yield tables for black spruce developed by Smith (1983) were used because they showed negative growth at the overmature stages, unlike the increasing volumes shown in Plonski (1981). This more accurately describes natural growth of black spruce.

The volume figures from the tables reflected full stocking. As discussed in Bell et al. (1989), this is not recommended for use in the real forest since rarely do planted stands fully occupy a site. Deductions for unproductive land and mixedwood or undesirable components can reduce projected conifer volumes by 25-60% in a given area. When this process is used in an actual forest, these deductions must be considered. For this analysis, a comparison of relative values was sufficient to outline the utility of this crop-planning process.

Determination of Spacing-Regime Objective

For simplicity, the number of trees planted per hectare was considered to be the level of well-spaced trees per hectare surviving at the free-to-grow stage. The field assessment for planted spruce sites was assumed to find natural regeneration to be equal to plantation mortality. In a real forest, the spacing objective formula would change by site or forest class due to varying amounts of ingrowth and mortality.

Wood Quality

For both pulpwood and sawlog revenue calculations, intrinsic and extrinsic wood quality factors were not considered. In a localized analysis, specific-gravity differences among spacing regimes could reduce merchantable fibre yield up to 10%. Moreover, extra revenue which might be generated by large tree sizes was also disregarded in this analysis.

Economic Assumptions

Economic Formulae for Forest-Class Analysis

To assess investment efficiency or quality, the two economic tools or yardsticks of BCR and PNW can be described with the following formulae:

a) Net Revenue Analysis

$$\text{Present Net Worth} = (B - C(1+r)^t) / ((1+r)^t - 1)$$

PNW is the quantity of total discounted revenue less establishment costs.

b) Benefit/Cost Ratio = $B / ((1+r)^t - 1) / C(1+r)^t / ((1+r)^t - 1)$

BCR is the ratio of discounted total revenue to costs.

For the equations,

B = PNW benefits (harvest revenue) received

C = PNW of costs

r = rate of discount

t = harvest age

In both cases, the length of the investment was standardized to an infinite duration. If the net-revenue yardstick is used, then the optimal project is that which produces the largest amount of "profit" over an infinite number of rotations. Otherwise, the silvicultural regime which produces the largest BCR is preferred.

Economic Formulae for Forest-Level Analysis

a) Total Net Revenue (annual)

Total Net Revenue for Forest = sustainable harvest volume times value per cubic metre minus annual management costs (silviculture and/or harvest costs) to maintain sustainable yield
 *Note harvest costs not used in this paper.

Net Revenue Gained due to silviculture (annual) = value increase in annual sustainable harvest (due to silviculture input) minus annual management costs

b) Benefit-Cost Ratio

This is based on only the total revenue increase due to silviculture, not total net revenue produced.

$$BCR = \frac{\text{Total Revenue Gained per Year}}{\text{Annual Management Costs}}$$

BCR, like net revenue, does not use discounted costs since the allowable cut effect is immediate with changes in silvicultural input.

Real Rate of Inflation

Throughout the analysis, a 4% real discount rate (no inflation) was used. This rate was based on historical standards. All prices and costs were expressed in 1988 Canadian dollars, unless otherwise specified.

Revenue Overview

All examples used revenue or delivered product prices (not net profit) to measure returns from silvicultural expenditures. This reflects the province's desire to manage the forests for the benefit of all citizens of Ontario. The price per unit of pulp or per fbm of lumber is composed of taxes and profits to various agents (the province, the harvester, the mills, transporters, and distributors) as well as the costs of the material, energy, and labour that go into the manufacture and distribution of wood products. The profits and costs of employment, energy, and material are assumed to reflect the amount of benefit to the provincial economy. As such, the product price represents the approximate value of provincial benefits generated.

Pulpwood Revenue Calculation

In the pulpwood scenario, entire stands are cut for pulpwood. The merchantable fibre volume is assumed to be used to produce bleached Kraft pulp. The ten- year average price from 1978 to 1987 for bleached Kraft pulp was \$775/tonne. This value is based on yearly pulp prices from the Canadian Pulp and Paper Association (1988) adjusted for inflation and U.S./Canada exchange rates published by the Bank of Canada. Approximately five cubic metres of wood are required to produce one tonne of bleached Kraft pulp (Hynard 1984; Anderson and Bonsor 1981). The revenue derived from one cubic metre of wood is \$155.

Sawlog Revenue Calculation

A sawlog produces both lumber and chips. The lumber yields from a log are typically determined using scaling methods called "log rules". For this analysis, several methods (including the Ontario rule) were examined but the International 1/4 inch rule was used (Chapman and Meyer 1949).

Honer's (1967) regressions were used to convert gross total volume/ha (based on an average diameter and merchantable height) to M board feet/ha (Figure A1). Honer's tables were based on a log length of 16 feet (1 foot stump, four inch top). There was a concern that significant taper over the length of merchantable bole could bias the recovery; however, Honer (1967) took this into account in the tables. By sawing the shorter log length in the mill, which is commonly the case, yields will be maintained or even increased (Gevorkiantz 1949). Furthermore, a conical approximation was tried using both log rules, but it consistently underestimated the lumber yields estimated by Honer's (1967) regressions. The conical approximation was also compared to taper factors for average trees in the Lake States and was found to overestimate bole taper (Gevorkiantz 1949).

How much revenue does this lumber generate? Data From "Random Lengths" (1987) were used to derive 10-year average prices for spruce-pine-fir studs and random lengths (2" X 4") delivered to Toronto. In northern Ontario, it was assumed that there is a fifty-fifty split between random-length lumber and stud production. The resulting average price was \$420 /Mfbm.

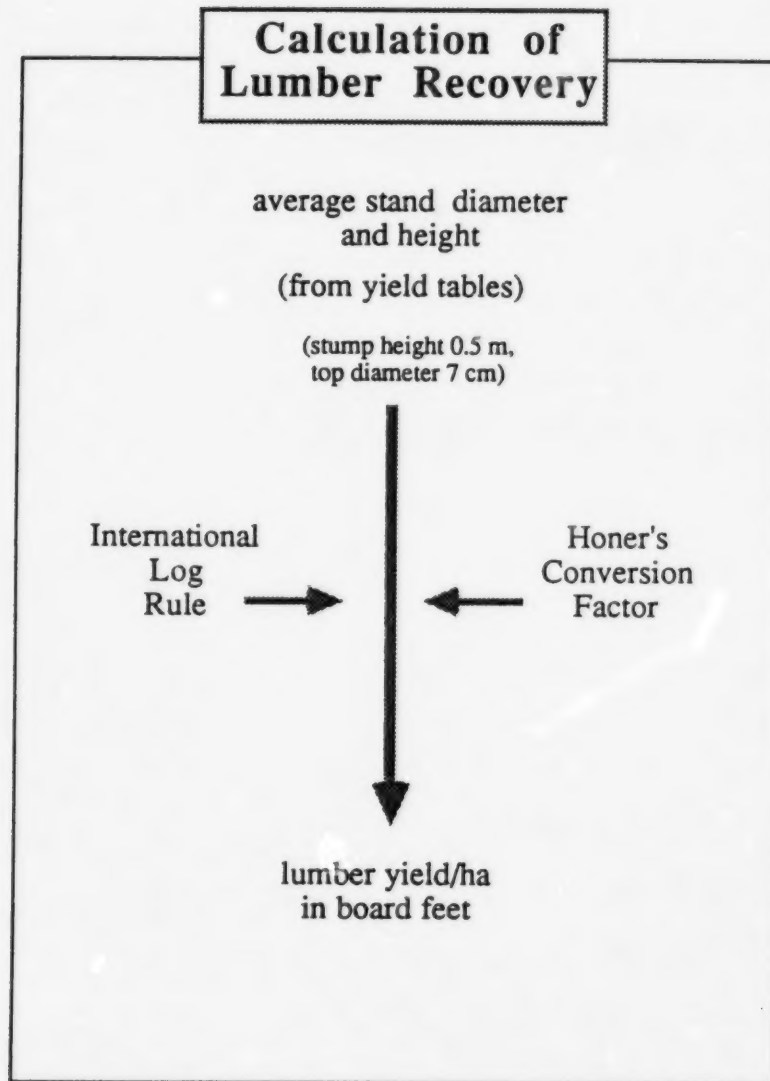


FIGURE A1. Calculations of lumber recovery.

How much revenue do sawmill chips produce? One oven-dry tonne (ODT) of chips contains 1000 kg of wood fibre. If the pulping process is 42% efficient, then 2.38 ODT of chips are required to make 1 ODT of pulp. However, since pulp is sold on an air-dry basis (10% moisture content), only 2.15 ODT of chips are required. Thus, one ODT of chips creates a value of \$360 when converted to pulp. Alternatively, the final-product value per cubic metre of wood chips is estimated at \$165.

Finally, to determine total revenue from sawlogs, the relative proportions of chips, sawdust and lumber must be known. To determine this, we assumed that 7% of the total merchantable volume was lost to sawdust, based on a study which determined that 20% of the log volume was reduced to sawdust when sawn by a 3/8" blade (Kerbes and McIntosh 1969). Since modern blades average 1/8" wide, production of sawdust should be 7%. Thus the volume of chippable wood equals the merchantable volume, less lumber production, less loss to sawdust.

Silvicultural Treatments and Costs

The silviculture system assumed was clearcut harvesting, mechanical site preparation, planting at various spacing regimes, and tending through aerial application of herbicide.

This silvicultural treatment regime was used to show the significant variability in economic efficiency when planting density is varied. For simplicity, the trees planted, based on northern Ontario averages, were assumed to achieve the same spacing regime as originally established; this assumes a compensating effect of natural regeneration and planted tree mortality. The mortality was assumed to be the same, irrespective of spacing, as found in other spacing trials (Omule 1988).

The components determining number of free-to-grow trees/ha (see Figure 3) consist of the number of trees/ha planted, plus ingrowth minus mortality (all in number of well spaced trees/ha). For most forest classes in management units in Ontario, appropriate values for this formula are not well known because regeneration survey data collection by site type is not common. Without knowledge of these numbers, overplanting or not planting enough trees is very possible.

The same set of silvicultural costs was used for all three case studies.

The "assumed" planting program consisted of mechanical site preparation over the entire planting area followed the next year by planting 62.5% container stock and 37.5% bareroot (northern Ontario average) and tending the area with an aerial application of herbicide five years after. (Note: many stands do not require any tending while some require tending one to two years after establishment - this is only an example.)

This "average" silvicultural regime was derived from Ministry of Natural Resources Expenditure reports for 1985/86 and 1986/87. The stock cost for various levels of spacing (Table A1) is the only cost assumed to change with spacing. The stock cost is based on the assumption of 75% site occupancy after planting (present level of operational planting).

Seed was assumed to cost \$3 per 1000 trees produced. The stock cost, \$185/M trees, was obtained by pro-rating the costs of bareroot stock (\$250/m) and container stock (\$146/m) by the relative percentage used for each type.

TABLE A1: Stock-cost calculation summary (\$/ha).

Spacing (m)	Full Occupancy No. Trees/ha	Actual Planting	Seed Cost	Stock Cost	Stock & Seed
1.8	3,265	2,450	7.35	453.25	461
2.0	2,500	1,875	5.63	346.88	353
2.5	1,600	1,200	3.60	222.00	226
3.0	1,111	833	2.50	154.11	175

The cost as given above and the other associated costs for 1.8 m spacing are displayed in Table A2. These costs are based on the Ministry of Natural Resources financial reports and expressed in 1988 dollars.

The present net value of establishment costs for other spacing regimes analyzed are listed in Table A3.

TABLE A2: Derivation of establishment cost of 1.75 X 1.75 m Spacing (\$/ha).

Activity	1988 Cost (\$)	Frequency	Year Relative To Estab.	Discounted Cost (\$)
Site Preparation	254.73	100%	-1	264.92
Stock Cost	460.60	100%	0	460.60
Planting				
Container	335.30	62.5%	0	209.56
Bareroot	412.40	37.5%	0	154.65
Chemical Tending	102.68	100%	5	84.40
TOTAL				\$1,174.13

TABLE A3: Discounted (to 1988) establishment costs for four spacings (\$/ha).

Spacing (m)	Cost (\$)
1.8	1,174
2.0	1,066
2.5	939
3.0	870

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APPENDIX B

Effect of Stand Density (Spacing Regime)
on the Growth, Timing of Harvest,
and Establishment Costs of Coniferous Stands
- A Literature Review -

Overview

The forest-class analysis determines the most cost-efficient spacing-regime objective. These objectives dictate future competition levels among crop trees, thus influencing the quality, timing, and quantity of the product produced. These future attributes of a stand are determined using the appropriate variable-density growth function.

The following text outlines some of the basic effects that spacing regime (density) has on the growth, timing of harvest, and establishment costs of the stands produced. An understanding of these concepts is crucial for crop planners to understand the consequences of setting different spacing regime objectives.

Effects on Volume and Diameter Growth

Based on Mar:Moller (1947)'s work, Smith (1962) made the following generalization: "The total production of cubic volume by a stand on a given site is, for all practical purposes, constant and optimum for a wide range of density or stocking. It can be decreased, but not increased, by altering the amount of growing stock to levels outside this range". This hypothesis refers to a given species and given site productivity. The same idea was expressed graphically by Langsaeter (Figure B1) (from Smith 1962).

A logical corollary of this theory is that mean diameter achieved at any given age varies directly with spacing regime (Sjolte-Jorgensen 1967). A manager can only grow one maximum level of gross total volume on a site, but this volume can consist of a lot of little trees, a few big ones, or any number of variations between (Figure B2). In summarizing a number of spacing trials of various species in Europe (Figure B3), Sjolte-Jorgensen (1967) showed that, almost invariably, wider spacings yield significantly higher average tree diameters.

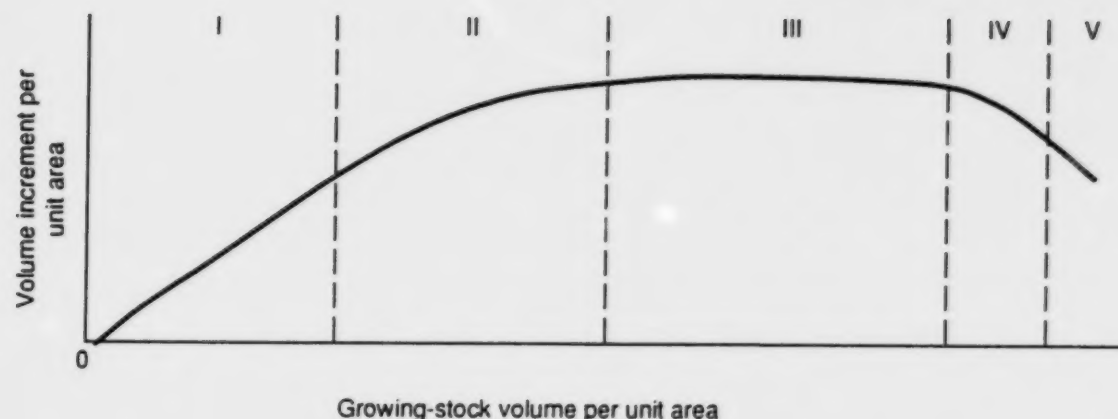


FIGURE B1. Relationship between growing-stock volume and volume increment. In Density Type I, the trees are so far apart that they do not influence each other and growth is directly proportional to the volume of growing stock. The effect of slight competition in Density Type II is indicated by a declining rate of increase in increment with respect to stand volume. In the broad range of stocking indicated by Density Type III, increment of cubic volume is virtually independent of variations in stocking; the usual objective of thinning is to keep the growing stock somewhere within this optimum range. In Density Types IV and V, the effects of extreme competition are reflected in a decline in growth with increasing density. (Smith 1962).

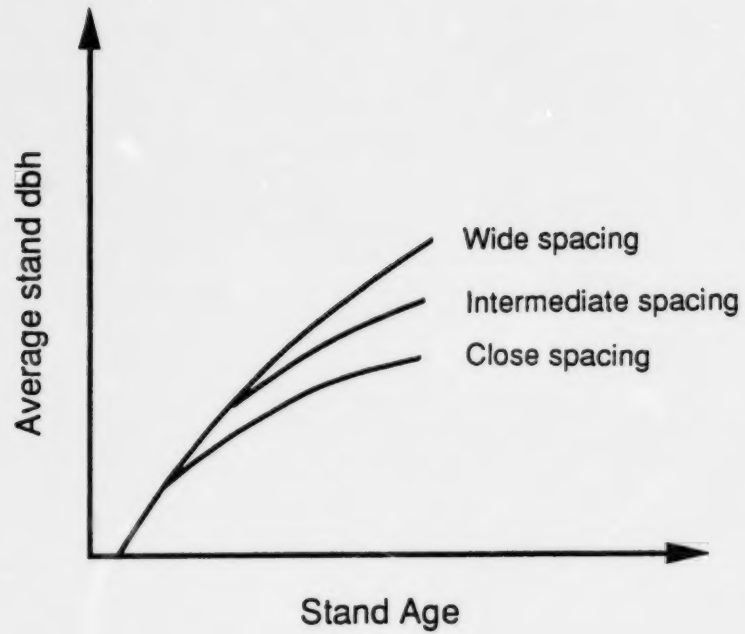


FIGURE B2. Development of average stand DBH in plantations over time at various densities (Clutter et al. 1983).

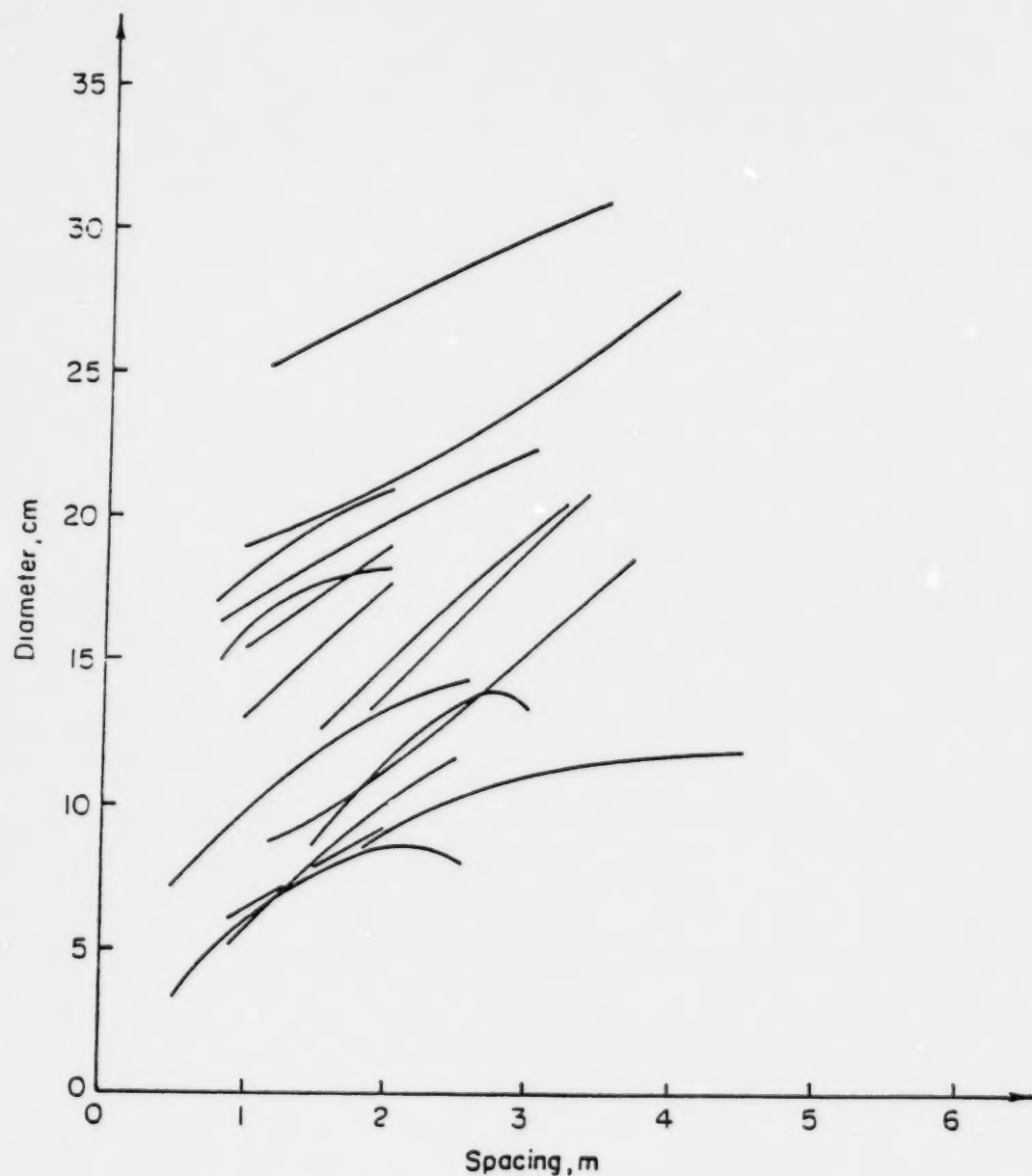


FIGURE B3. The relationship between mean diameter and spacing for coniferous tree species (Sjolte-Jorgensen 1967). Each line represents a spacing trial and the associated diameter-versus-spacing relationship.

Baskerville (1962) hypothesized that "annual production increases with increasing density up to the point where the stand achieves full occupancy of the site...At densities greater than full occupancy, the utilization is still maximum..." In simple terms, this means that stands established with a wide variety of spacing regimes will have similar volumes once they all have attained full site utilization. This concept is supported by a large amount of literature, e.g. Baskerville (1962), Smith (1962), and Nawitka Resource Consultants Ltd. (1987).

Figure B1 clearly shows that this hypothesis has its limits. In density type 1, the stand densities never fully occupy the site and the maximum net growth potential of the site is never reached. The minimum tree density for full occupancy has not been determined for boreal species. For Douglas-fir, Mitchell and Cameron (1985) estimate this density to be 300 trees/ha at maturity. For Nova Scotia conifers, maximum site productivities in total $m^3/ha/yr$ for 1.5 m and 4.0 m spacings are roughly equivalent (Anon. 1988).

As for the upper level of densities, no one has determined the density at which growth of boreal species is impeded. However, very dense, fire-origin lodgepole stands (more than 20,000 stems/ha) in British Columbia are commonly referred to as growth-impeded.

Smith (1962) described early beliefs that very dense stands would tend to maximize the merchantable volume and wider spacing through thinning would actually tend to increase the merchantable volume. Smith (1962) stated that these beliefs could have been based on various imprecisions of measurement as far as total growth is concerned. Does this mean that yield (merchantable volume) from natural stands will be equivalent to managed stands? Figure B4 shows instead that the merchantable volume of natural stands is significantly

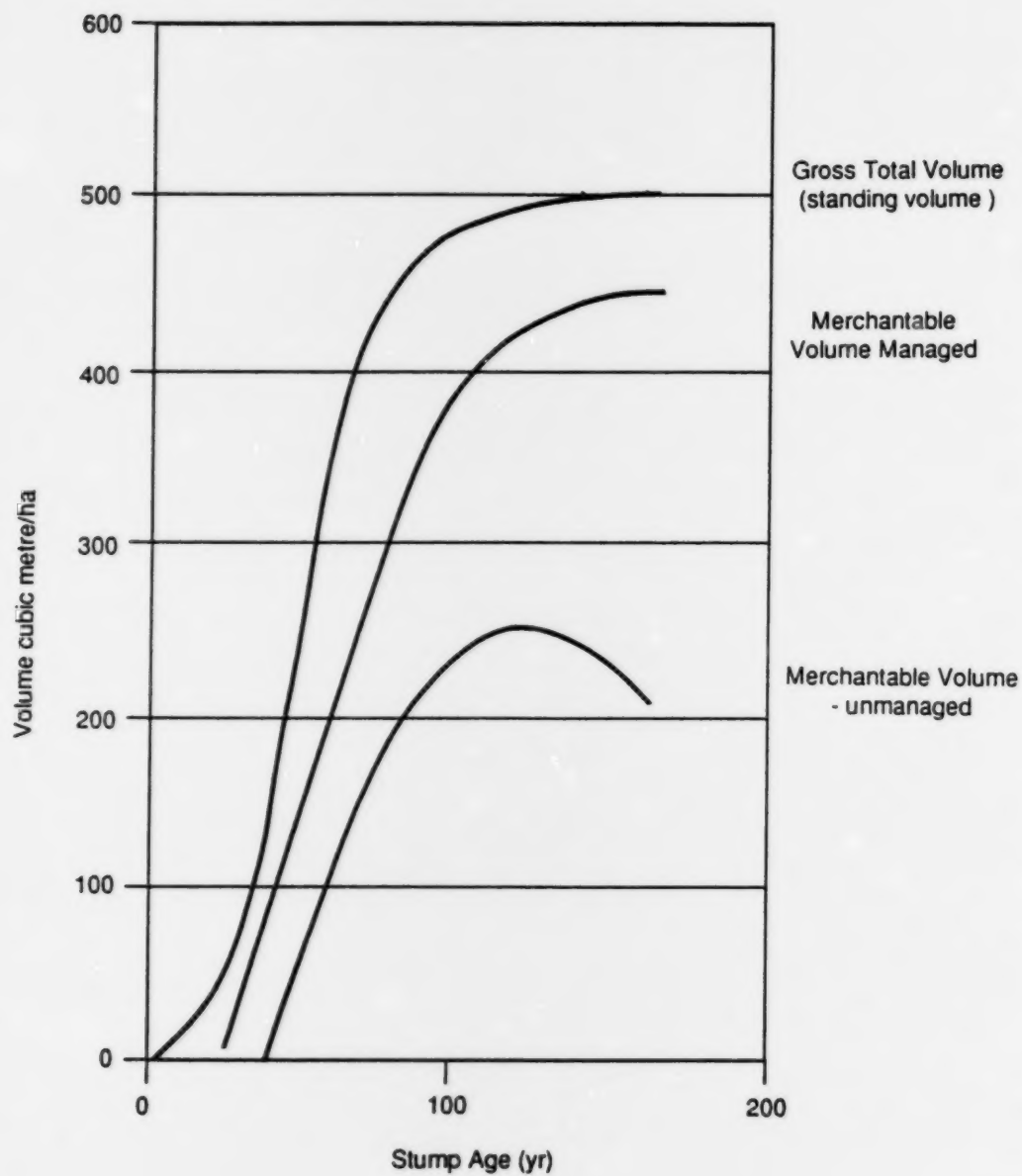


FIGURE B4. Conceptual comparison of gross merchantable volume of managed stands versus unmanaged stands.

lower than managed stands given equal ages. The gross total volume (merchantable and unmerchantable tree volume - Figure 8) in natural stands is roughly equivalent to that of managed stands, but the merchantable volume is lower because the intense competition in natural stands due to the thousands of stems initially established produces many small-diameter trees that are unmerchantable.

Although standing total volume (gross total volume) may be the same, total stand production over time in the closer-spaced plantations and natural stands may be slightly higher than in wider-spaced stands, because full site occupancy occurs quicker (Assmann 1970). Unfortunately, most of this fibre is lost to mortality, especially in the case of the natural stands. This loss can be partially offset if the stands are spaced to leave some growing space temporarily unoccupied. In Europe, much of the fibre in dense stands are utilized by multiple thinning thus resulting in higher merchantable stand productivity (Assmann 1970).

Timing of Harvest and the Relationship to Stand Density

The forest analysis in the crop-planning process will help a manager determine when wood shortfalls may occur. Crop planning attempts to determine how additional wood can be grown in time to cover the shortfall.

Density affects stand growth in that narrower plantations achieve full site utilization sooner than wider spaced plantations (Figure B5). The total growth $m^3/ha/yr.$ in the closer-spaced plantations first exceeds and then falls below that of the wider spaced stands (Figure B6). This has been shown by 38-year measurements at the Thunder Bay Spacing Trials (Anon 1989), and also in coniferous plantations in Nova Scotia (Anon 1988)

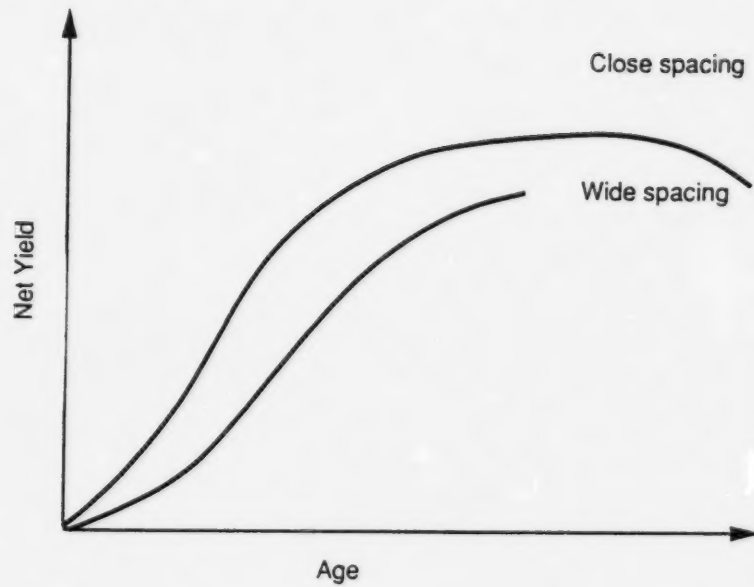


FIGURE B5. An illustration of stand density effects on net yield (total volume) as observed in spacing experiments in even-aged stands (Clutter et al. 1983).

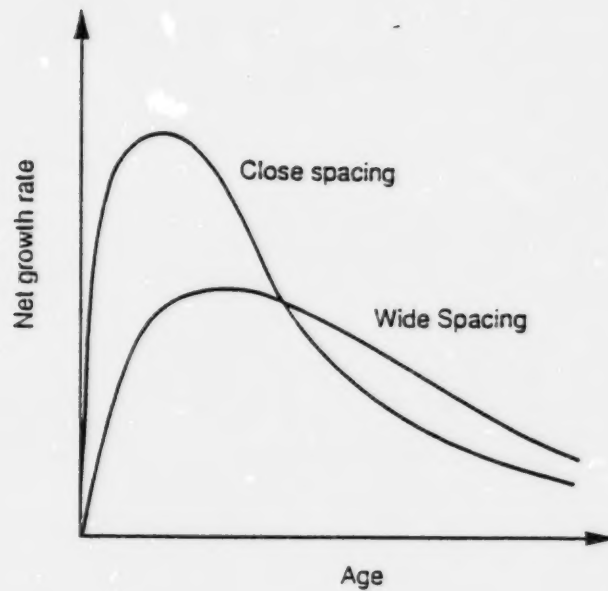


FIGURE B6. An illustration of stand density effects on net growth rate of total volume as observed in spacing experiments in even-aged stands (Clutter et al. 1983).

Closer-spaced plantations produce biomass in a quicker period of time but, wider-spaced plantations can produce economically operable stands in a quicker period of time. Stand operability is an economic determination (not biological) that depends on both minimum size of trees that can be harvested economically and minimum merchantable volume per ha required. These flexible merchantability limits determine minimum stand age of harvestability. Figure B7 shows a merchantable growth curve for both a close and wide-spaced plantation. As in the total growth curves shown in Figure B5, the closer-spaced plantation initially achieves volume at a greater rate than the wider-spaced plantation. However, if the minimum operable volume per ha has been set at 50 and the tree size must represent at most, 15 stems per m^3 , then the wider-spaced stand would be operable sooner (i.e. 35 years versus 46 for the closer-spaced stands). Causing this, is the biological reality that trees in wider-spaced plantations have faster diameter growth than closer-spaced plantations and achieve operable piece size sooner.

Alternatively, if forest stands could be economically harvested somewhat like corn, and the only criteria was minimum merchantable volume of 50 m^3 /ha, the closer-spaced plantation would be operable at 25 years versus 35 years for the wider-spaced plantation.

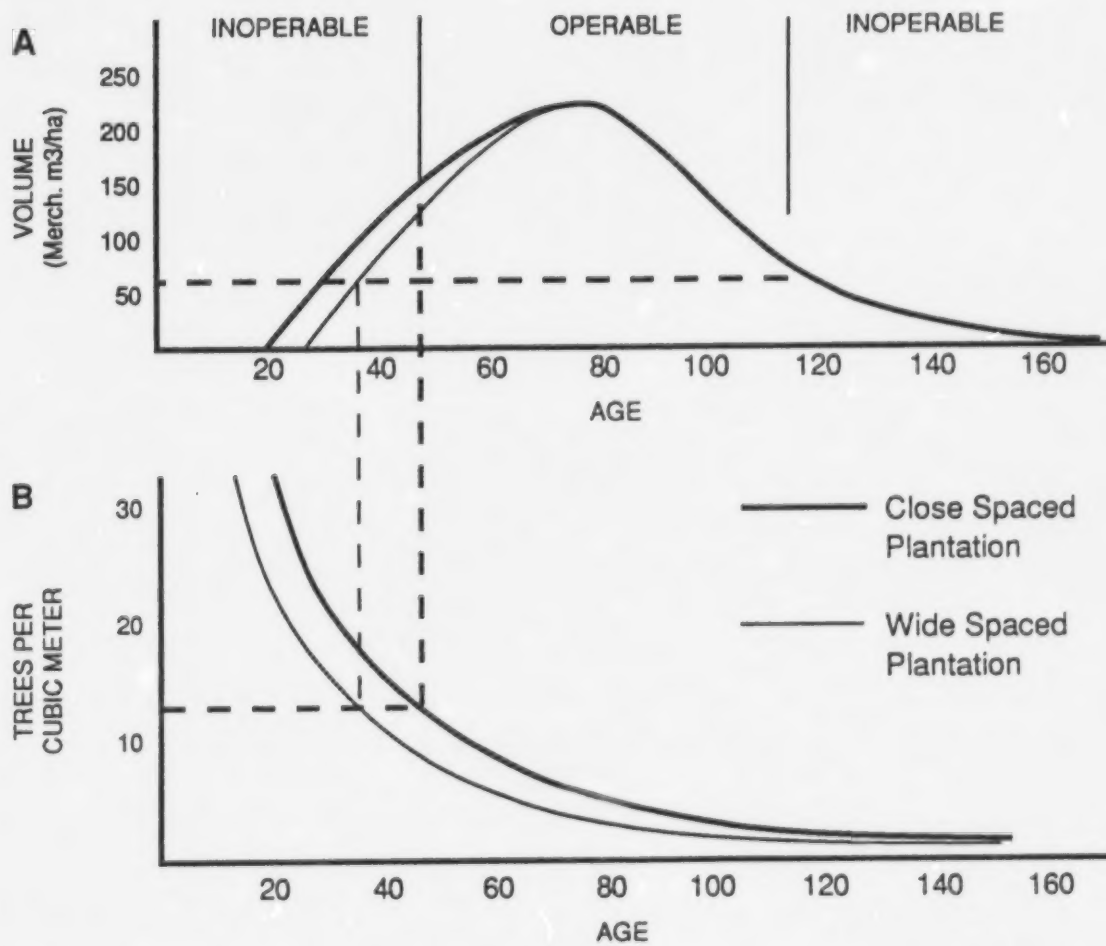


FIGURE B7. The influence of spacing, volume, and tree size on forest stand operability.

In comparison, dense natural stands (i.e. 10,000 - 100,000 stems/ha) achieve operability much later (and with much reduced merchantable volume) than the less dense plantations (i.e. 1000 - 3000 stems/ha). It's common for most trees in dense natural stands to die before they reach merchantability. In dense natural stands, much longer rotations are necessary in order to grow operable stands or even stands with minimum merchantable volumes. Baskerville (1962) stated that when spacing control is implemented, the stand volume and average tree size characteristics of a natural stand can be reached in perhaps one half the time of natural development.

Density Management Diagrams --- A Crop Planner's Aid

The previous sections outlined many factors that a crop planner should consider when developing the most effective silvicultural ground rules. Very important is the relationship of average tree size (piece size) and density of the stand. The relationship of piece-size and density is critical, especially when determining timing of harvest. Several authors (e.g., Drew and Flewelling 1979) have developed density-management diagrams that conceptualize the density-driven stand dynamics that have been discussed earlier. For example, Smith and Brand (1988) developed a red pine density diagram (Figure B8). It has mean tree volume on the vertical axis and number of trees/ha on the horizontal axis. The basic idea is that the stand can either have a lot of little trees or a few big ones but the same stand volume. Also plotted are diameter and height isolines which make this diagram (Figure B8) a four-dimensional model.

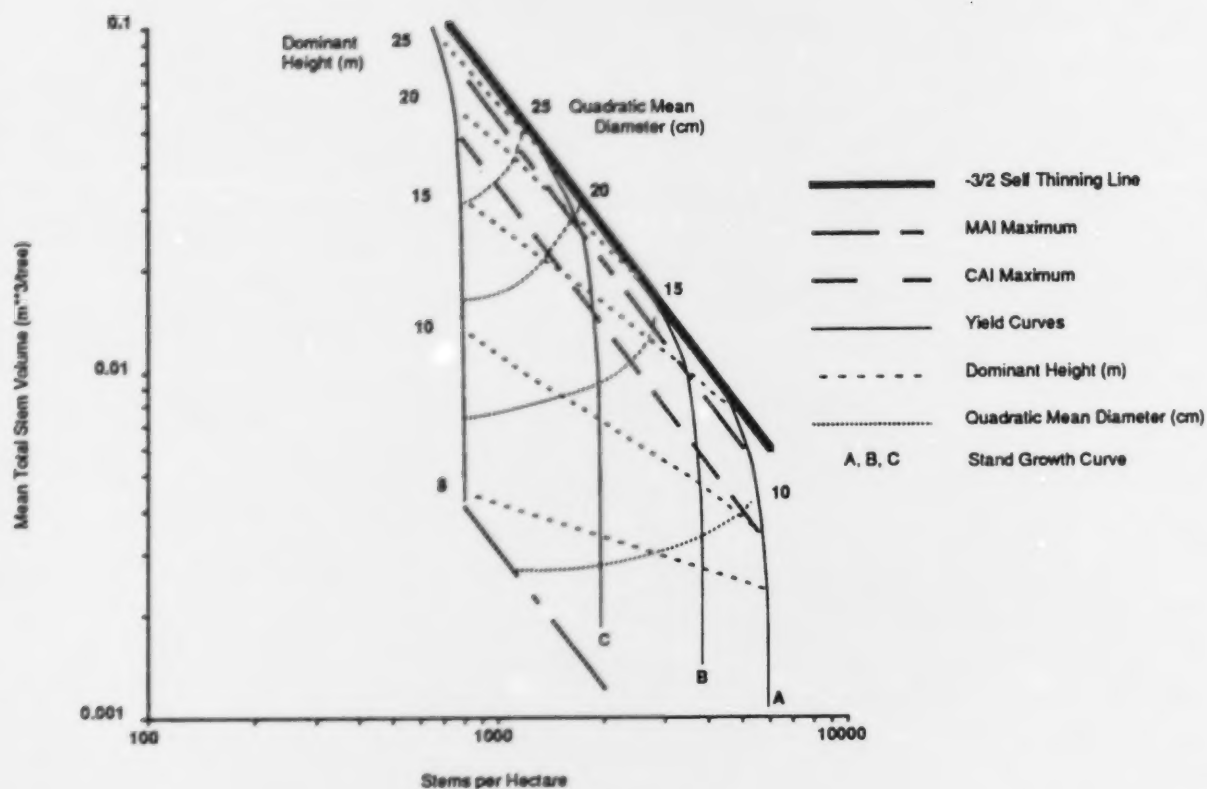


FIGURE B8. Stand-density diagram for red pine (adapted from Smith and Brand 1988).

The slope of the line ($-3/2$ self-thinning line - applicable for all species) designates the largest number of trees of a given size that can occupy a hectare at any one time. The "x" intercept is said to be independent of site and age but dependent on the competitive physiology of each species. The diagram and line are based on work by Yoda et al. (1963) who found that mortality from intraspecific competition (i.e. self thinning) had the following relationship:

$$\ln w = a - 1.5 \ln N$$

where

$\ln w$ = natural log of mean weight of survivors

$\ln N$ = natural log of number of survivors

a = regression co-efficient.

Simply stated, in pure, even-aged stands of plants, the maximum production is the same at full stocking, regardless of initial density; however, full occupancy occurs at different ages depending on initial density. This concept is yet another statement of Mar:Moller's hypothesis.

In Figure B8, the 3 diagonal lines parallel to the $-3/2$ line show the relative density index (RDI) defined as the actual number of stems of a given mean volume over the maximum number of stems of the same given mean volume. These 3 RDI lines have been labelled crown closure, CAI and MAI Maximum. Each represents stand-development phases which can be expressed in RDI values. For instance, the RDI value for crown closure in Douglas fir is 0.15 while maximum MAI is 0.55 (the point where significant mortality is caused by competition).

On Figure B8, three growth curves (A,B,C) are plotted. Note the faster site utilization of the denser natural stand (initial density 6,000 stems/ha), achieving maximum MAI at height 10 m, whereas the plantation at 2,000 trees/ha reaches this same point at 16 m. However, for the dense stand, the average

diameter at full site utilization is only 13 cm while the plantation is almost 20 cm.

Consider the height isoline as a function of time (age). If the site quality (class) of the plotted yield curves are known, then age can be determined. This type of relationship can allow the forester to predict the age at which operable tree size will occur for various densities. For example, consider an operable size of 15 cm for red pine. This size is reached at 11 m height for plantation C (initial stocking 2,000 stems/ha) and 18 m height for stand B (3,800 stems/ha). If both yield curves are site index 18, then these heights correspond to 30 years for plantation C and 55 years for stand B. The key here is that for a given operability limit, the harvest window is strongly influenced by density.

Although the relationship between mean tree volume and stand density is solid, and it is effective to determine change in tree size versus stand number over time, it can be dangerous if the results are used literally rather than conceptually. Cameron (1988) noted that stand volumes obtained by multiplying number of stems times mean tree volume along a growth curve) for Douglas fir are grossly over estimated.

Baskerville (1989) suggested that the diagram's four dimensional relationships (density, average tree volume, average height, and diameter) are not linear and plotting them gives questionable relationships. Also, the major assumption that height is independent of stand density is unrealistic, especially for very dense natural stands. The result of these two problems is that assigning ages to a plotted stand trajectory (yield curve) can be very inaccurate unless specific knowledge of the stand trajectory is known. Thus, the volume per hectare calculated from the tree of mean DBH and height is not the same as

the stand volume obtained from multiplying the number of stems by mean tree volume. This relationship on the density diagram makes its use very dangerous for estimation of stand volumes.

Silvicultural Costs

Once again referring to the density objective equation (Figure 4), one of the forester's objectives is to minimize the amount of funds spent on establishing the artificially regenerated portion of new stands. Also important is that a closer-spaced plantation loses trees over time at a much quicker rate than a wider-spaced plantation (Clutter et al. 1983) (Figure B9). In fact, theoretically, over time, the same number and size of trees will occupy the site in the end (Clutter et al. 1983), although this theory is disputed by some authors (e.g., Cameron 1988).

Consider Berry's (1987) white-spruce spacing trials (Figure B10) and the plantations which were established at 1,500 trees and 2,500 trees per hectare. The cost for establishing a plantation at 2,500 trees/ha is \$1,174/ha and would produce 315 m³/ha at 60 years or \$3.72/m. For the 1,500 trees/ha plantation, the establishment cost is \$978/ha and would produce 290 m³/ha at 60 years or \$3.40/m. Thus, 20% of the cost of plantation establishment at 2,500 trees/ha produces only 9% of the merchantable volume. If there is a wood shortage and no piece-size operability limits, then the extra wood produced with the denser plantations at the higher cost may be favoured.

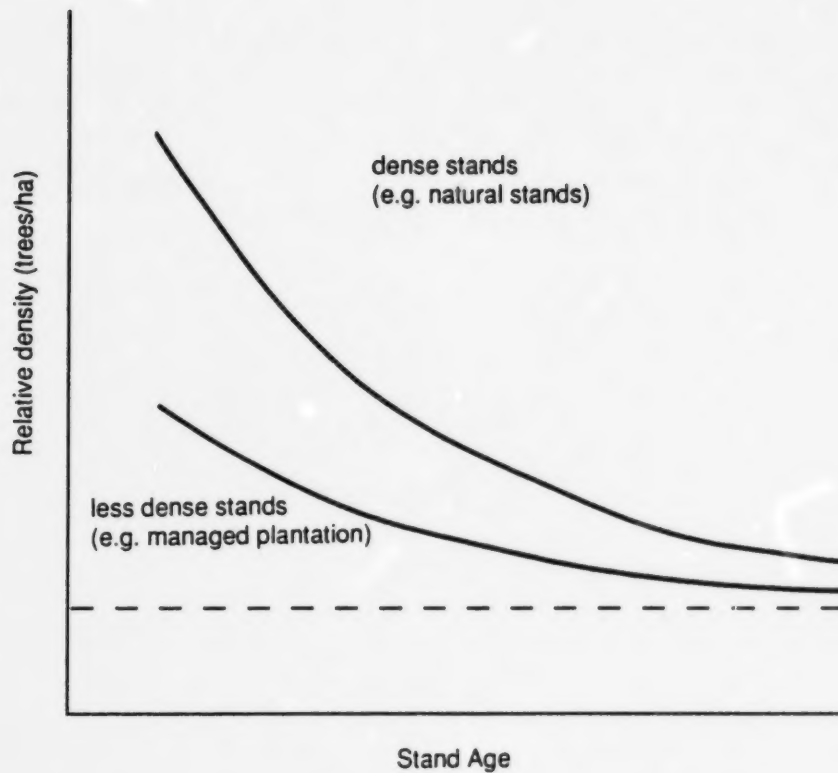


FIGURE B9. Changes in stand density over time for two stands established at different spacing regimes (adapted from Clutter et al. 1983).

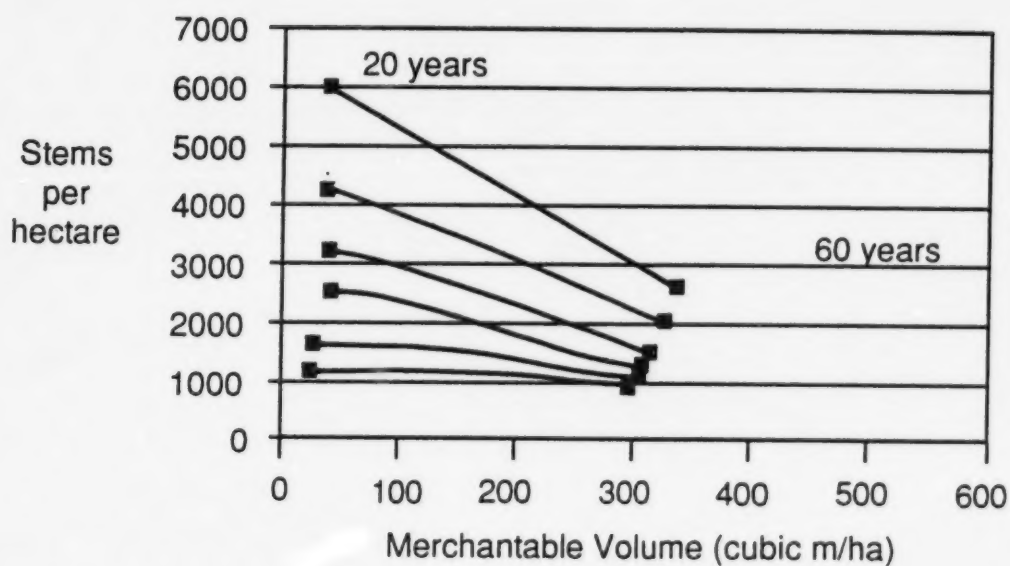


FIGURE B10. The relationship between stand density and merchantable volume of white-spruce plantations by five-year increments for site index 18 (Berry 1987).

A common fear of many Ontario foresters is that wider-spaced plantations will mean more weed control. There is little information in the literature relating spacing or density to amount of weed control. With one basic plantation-spacing regime, there is little experience in Ontario in comparing various spacing regimes. Butler-Fasteland (1989) stated that when Minnesota changed from a five-foot spacing regime to an average of eight-foot spacing, there was no significant difference in number of herbicide applications.

Consider black spruce plantations established at spacing regimes of 2.0 and 2.5 m respectively. For the first 10 or 15 years, the light and soil conditions for both plantations are the same. It follows that both sites have the same potential for interspecific (and even intraspecific from natural ingrowth) competition. The issue here, on brushy sites, is the need to properly release these young crops from competition as quickly as possible. The requirement for more than one herbicide application is dependent upon the amount of initial weed ingrowth and the efficiency of spray, not on the spacing regime objective.

The key effect of wider spacing is a later crown closure. For example, Site Class 1A black spruce may have a crown closure at age 20 when established at 2.5 m instead of age 15 when established at 2.0 m spacing. If proper weed control were applied within the first five to ten years of establishment, then any weeds initiated at age 15 should be little problem and will not require more herbicide treatments.

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APPENDIX C

Effects of Stand Density (Spacing) on Wood Quality

- A Literature Review -

SUMMARY

In Appendix B, effects of spacing on stand growth, size of individual crop trees, silvicultural costs and timing of harvest were summarized. Lower establishment costs, coupled with higher-value end products, with earlier availability at wider spacings, can offset the loss in total volume and make lower establishment densities attractive. However, early competition experienced in stand development not only influences growth rate, but also influences log quality for pulpwood or sawlogs. This ultimately determines the value of the crop produced. Most literature generally supports the theory that log quality varies directly with stand density. Narrower spaced stands have narrower rings, more late wood, and thus higher quality.

The variables used to measure log quality include intrinsic (internal) parameters such as ring width and specific gravity, and extrinsic (external) parameters such as stem diameter, log length, bole taper, and knot frequency. Although there are many studies comparing wood quality and spacing, few have evaluated fibre quality from Canadian plantations (Barbour and Kellogg 1988). Many reviewers have found wood quality information to be both contradictory and sparse for many species. Alternatively, we believe the literature shows definite trends for most of the important quality attributes. Briefly, quality attributes for both pulpwood and sawlogs do not seem to deteriorate dramatically with modest increases in spacing regime (e.g., 2.0 m to 2.5 m). In fact, when diameter and height are considered, overall quality may be higher in wider-spaced stands (especially for sawlogs).

The inherent differences between species and even races within species are not considered in this quality assessment. In his literature review, Bendtsen (1978) concluded that most wood characteristics, such as average fibre length

and specific gravity, are moderately to highly heritable. In one single cycle of selection, a 10% improvement in fibre length can be obtained. He also suggested that proportions of juvenile wood could be controlled without reducing growth rate. This is good news for jack pine growers who are faced with broad genetic variability in that species. Finally, if one assumes significant quality differences as a result of fast-growing, intensively managed plantations, then one should realize that most competitors in the forest products industry will also be adjusting to lower quality raw material (Bendtsen 1978). Although we believe that the literature favours the conclusion that small changes in spacing do not significantly reduce quality over a given rotation, there is concern that shorter rotations for plantations may have a significant impact on quality due to an increase in juvenile wood (see Janas and Brand's (1988) study and work cited in Sjolte-Jorgensen (1967)).

We conclude that small spacing changes (0.5 m) will not significantly affect wood quality. However, wood quality experts such as Barbour (1989) of FORINTECH are concerned that wood quality will be significantly compromised if the spacing regime difference is much wider (i.e. 1 m). Clearly, further studies are necessary to determine more accurately the wood quality tradeoffs associated with stand density changes.

Intrinsic (Internal) Variables

Wood strength is directly related to specific gravity (SG) or density of wood, and fibril angle (Bendtsen 1978). SG is considered the best single index of intrinsic wood quality (Bendtsen 1978). Variations in SG can have a significant impact on pulp yields. For example, an SG difference of 0.01 would cause a difference in the weight per cubic meter of dry wood fibre amounting to

10 kg (Baker 1967). Using an average yield of 150 m³/ha, this results in a 1,500 kg reduction of pulp yield. Also important in pulp manufacturing is the amount of compression wood. Compression wood has high lignin levels which reduces the chemical pulping yields (Hall 1963). The amount of compression wood is indirectly related to increases in fibril angle (Bendtsen 1978).

The basic factor affecting SG and fibril angle is the amount of juvenile wood in the log. Juvenile wood is characterized by a 10-15% lower SG and lower fibril angle than mature wood (resulting in lower pulp yields and wood strength). Juvenile wood is produced in a situation where the bole is surrounded by live crown. Maximum rate of juvenile wood growth occurs in the establishment phase when the trees are open-grown and have a full crown that is just beginning to recede from the ground. The rate of juvenile wood production decreases following crown closure and particularly when the crown significantly recedes from the ground. Juvenile wood is also produced in mature and overmature forests. It is not something new, being present in every tree cut and processed (Smith and Briggs 1986). The primary problem is that plantation trees in new forests are grown faster and harvested sooner, so the proportion of juvenile wood is higher (Bendtsen 1978).

Variations in SG and fibril angle, which depend mainly on relative amounts of juvenile wood, are influenced by genetics, stand development history, site, climate, competition, rate of growth, and extent of live crown (Hall 1964). Many of these factors can be controlled through density management.

What spacing variations would produce significant differences in SG? Work conducted by Erdmann (1988) showed that a 3.66 m spaced plantation will produce juvenile wood for approximately six years longer than a 1.83 m spaced plantation. Berry (1987) presented values for merchantable biomass production (a function

of SG) based on spacing regime and site (Figure C1). SG differences between 1.8 m and 2.5 m spacings are less than 10%. Baskerville (1962) stated that total dry-matter production (weight/ha) was the same for similar sites irrespective of stand density.

Sjolte-Jorgensen (1967) presented data showing similar trends for Norway spruce (Table C1). The 47-year-old Norway spruce showed a 10% higher SG at 2.0 m as compared to 3.5 m spacing (Sjolte-Jorgensen 1967). Jayne (1958) found smaller differences when he compared SG values of red pine plantations spaced at 1.23 m to 2.46 m. He concluded that site quality had a much greater effect on specific gravity. For southern pine (loblolly and short leaf), Maeglin (1967) found differences less than 5% between plantations of 1.1 and 2.5 m spacings.

What spacing variations would produce significant variations in compression wood? The only evidence we can find in the literature was for Norway spruce which showed no increase in lignin with increased spacing (Sjolte-Jorgensen 1967). High lignin content, which reduces pulp yield, is associated with compression wood (Hall 1963). Studies analyzing effects of small changes in spacing (2.0 m versus 2.5 m) on compression wood volumes are not available.

Other intrinsic variables that are important to wood quality and are affected by spacing include resin content, cell length, and transverse shrinkage. Bendtsen (1978) related these variables schematically (Figure C2) between juvenile and mature wood. Wider spacing tends to produce slightly lower quality values for most of the other intrinsic variables because of the increase in juvenile wood.

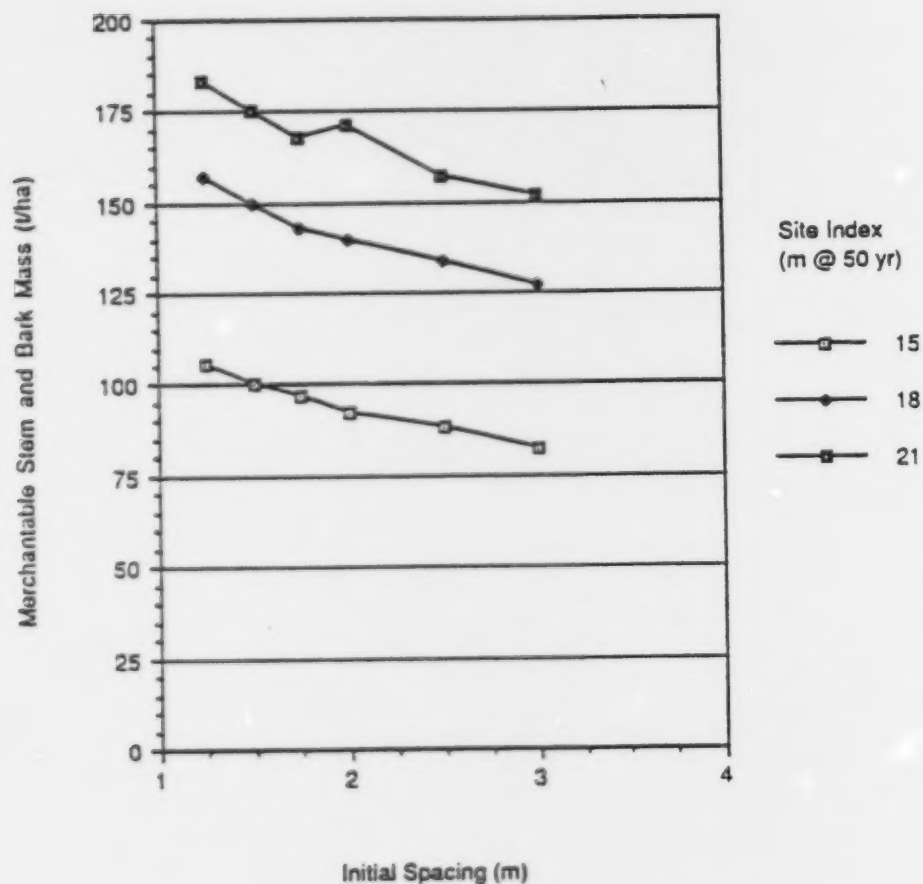


FIGURE C1. The influence of site quality and initial spacing on merchantable total biomass of unmanaged white-spruce plantations (Berry 1987).

TABLE C1: Stand characteristics of 47 Year-old Picea abies as influenced by initial spacing (data from Klem 1952, cited in Sjolte-Jorgensen 1967).

Spacing (m)	Mean Diameter (cm)	Taper Whole Stem (cm/m)	Percentage of Knots	Specific Gravity	Total Production (tonnes/ha)
1.25 x 1.40	20.1	0.98	0.191	0.415	261
1.40 x 1.65	20.5	1.02	0.236	0.423	240
2.00 x 2.00	24.1	1.04	0.260	0.419	218
3.00 x 3.00	26.0	1.13	0.340	0.385	218
3.50 x 3.50	28.3	1.26	0.335	0.384	166

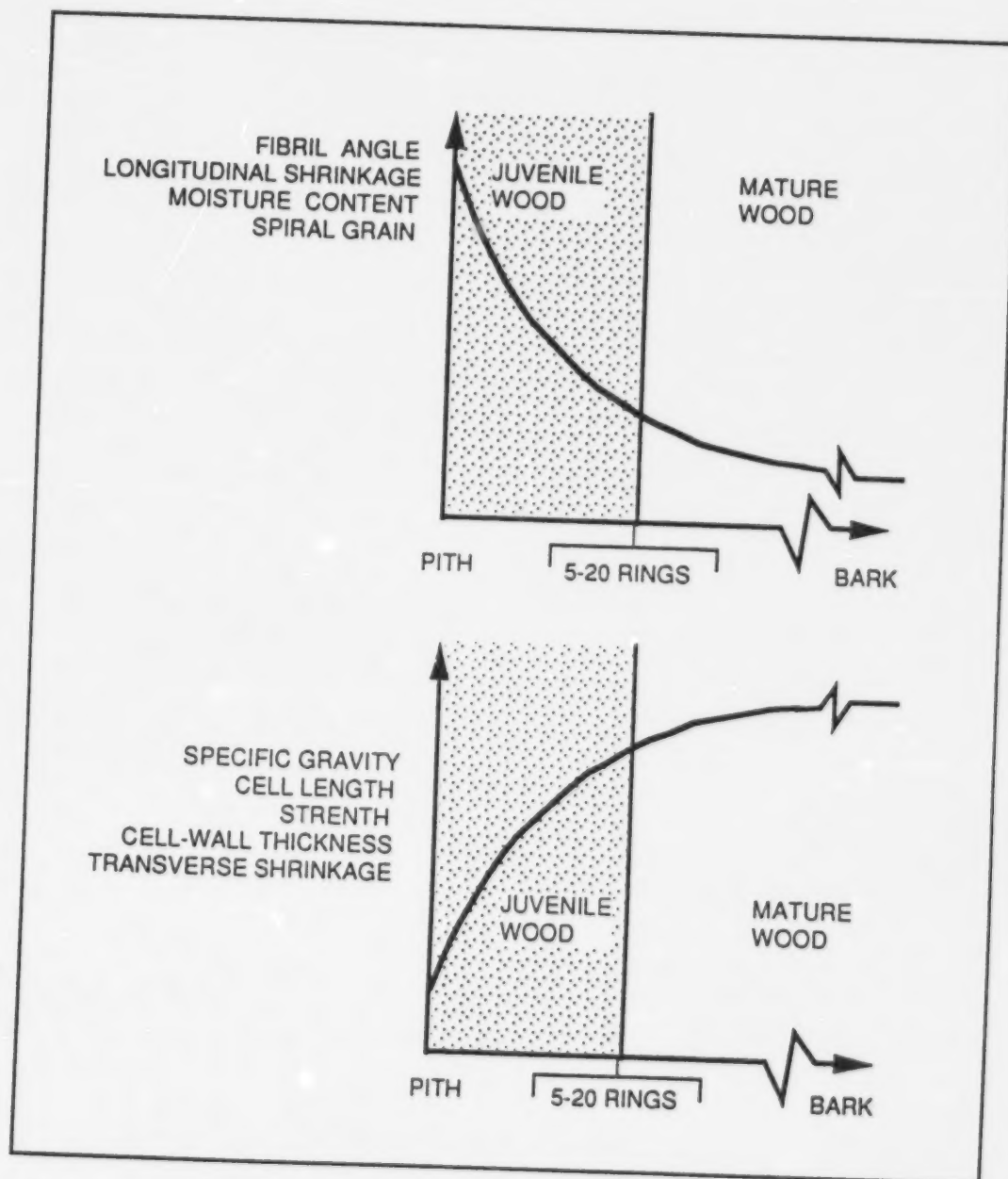


FIGURE C2. Schematic representation of the gradual changes in properties from juvenile wood to mature wood in conifers (Bendtsen 1978).

Ballard and Long (1988) noted many similar differences with intrinsic wood quality in the literature and concluded that other factors such as genetics may cause these inconsistencies.

Extrinsic (External) Variables

External quality indicators include diameter, height, taper, knot size, and branchiness. These factors are important if sawlog production is the objective.

Diameter varies directly with spacing. Studies by Gevorkiantz (1949) on boreal coniferous species showed that the higher the average stand DBH, the greater the proportion of sawlogs (Figure C3). Larger diameter logs yield significantly more revenue than smaller logs. Barbour and Kellogg's (1988) recent study for coastal species, which included individual log evaluation at the mills, showed significant increases in revenue with larger logs. This was also confirmed by Assmann (1970) who noted that 18 cm and 13 cm trees had values of 32.8 and 22.4 DM (German Marks) and harvesting costs of 15.2 and 18.8 DM respectively.

Height, the prime influence on log length, is also influenced by spacing. Some European studies showed that increased spacing up to an optimum level for the site will result in greater height (Sjolte-Jorgensen 1967). There are several studies showing no difference in heights or decreased height with increased spacing (Sjolte-Jorgensen 1967). For boreal species such as jack pine, total height is relatively constant over a wide range of spacings (Rudolf 1951; Bulger 1987; and Janas and Brand 1988) and variations in height among individual

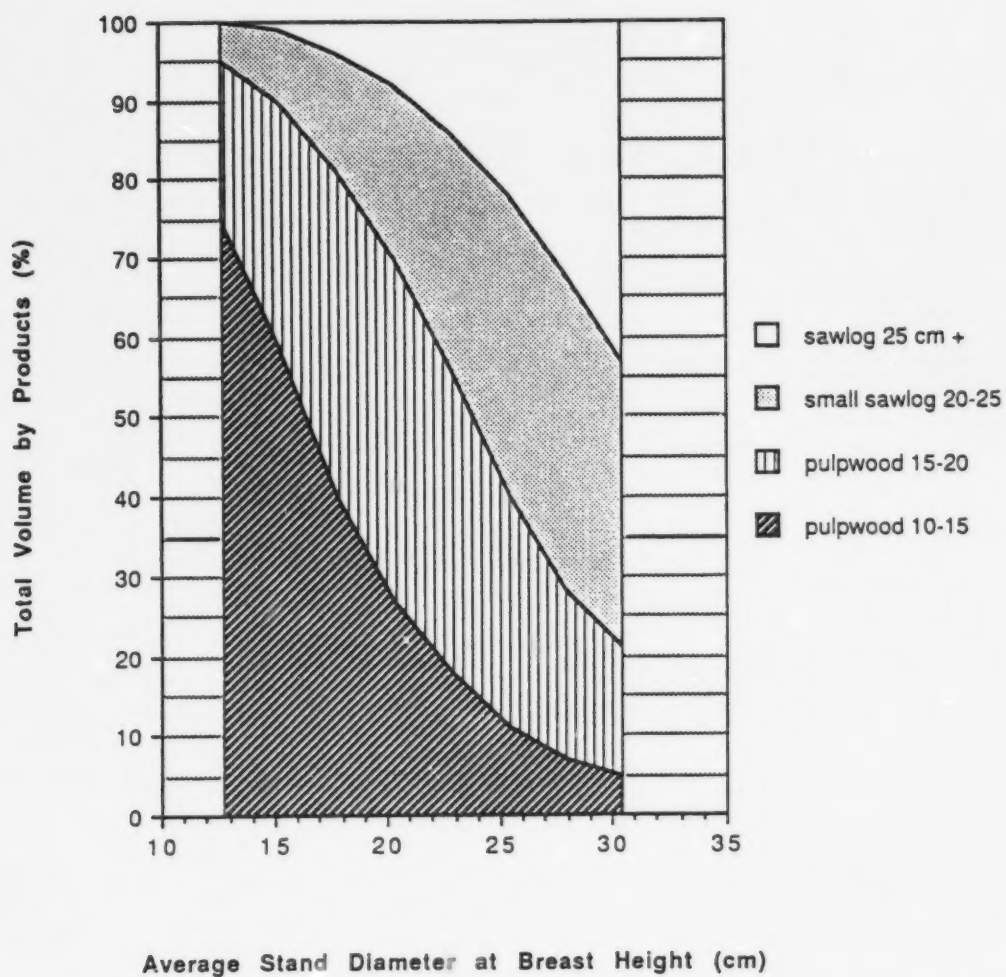


FIGURE C3. Proportion of various rough products in second-growth stands as a function of average tree DBH (Gevorkiantz 1949).

jack pine trees within a stand are generally small (Vezina 1964). However, height depression of jack pine does occur in both very low density and very high density stands (Chrosciewicz 1971). Figure C4 shows that jack pine, after 20 years of growth in northern Ontario, had little height variation over a wide spacing range.

Knot size is important for poles and lumber. The greater the proportion of knots, the lower the strength (Ballard and Long 1988) and the less high value clear wood produced. Spacing affects knot size by influencing the retention time of the live-crown's lowest branches (Steill 1964). Self-pruning occurs at the start of crown closure. The wider the initial spacing, the longer it takes to reach crown closure, thus increasing branchiness and knot size.

Ballard and Long (1988) clearly outlined the levels of branchiness relative to stand density for lodgepole pine (Figure C5). They also presented a relationship between the average diameter of the five largest branches in the first log and stand density (Figure C6). They concluded that initial stand density should be based on the largest acceptable knot size for a particular product. For example, a 2.5 m spacing will produce a maximum knot size of 2.2 cm while 1.8 m will produce a maximum knot size of 1.9 cm. For northern Ontario lumber, is that a significant difference?

Work on Norway spruce has quantified the basal area of knots as a percentage of the surface of the whole stem up to a 7 cm top diameter (Sjolte-Jorgensen 1967). From 2 m to 3 m spacing, the increase was only 0.08%.

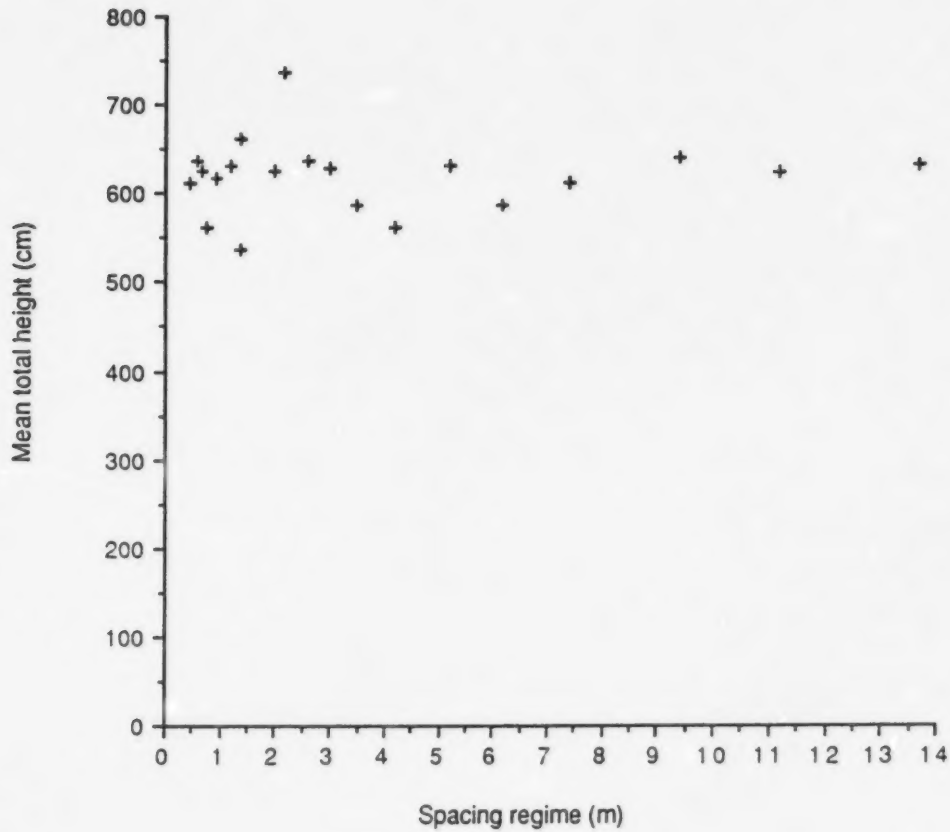


FIGURE C4. Scatter plot of observations for total tree height at age 19 over spacing for jack pine (Bulger 1987).

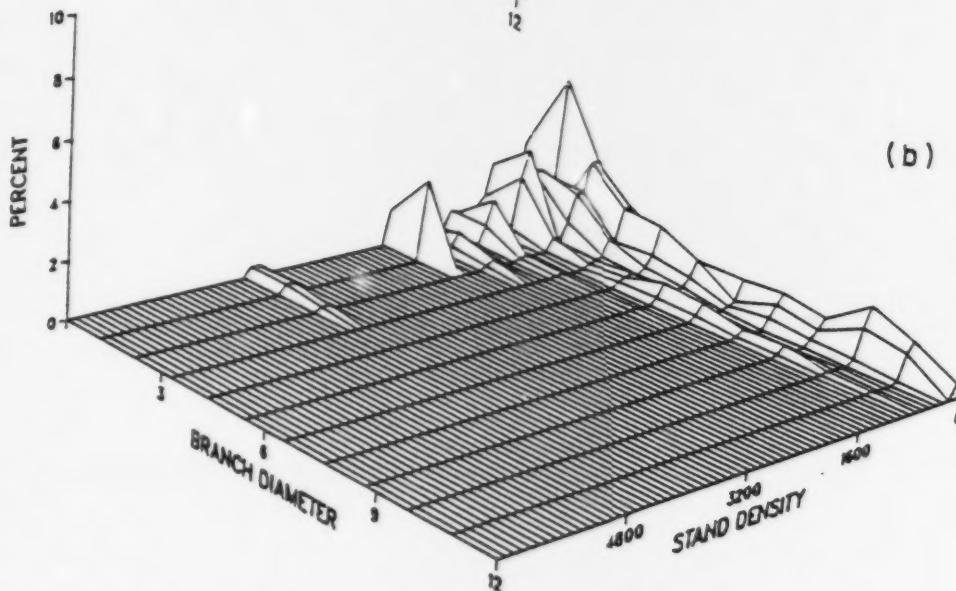
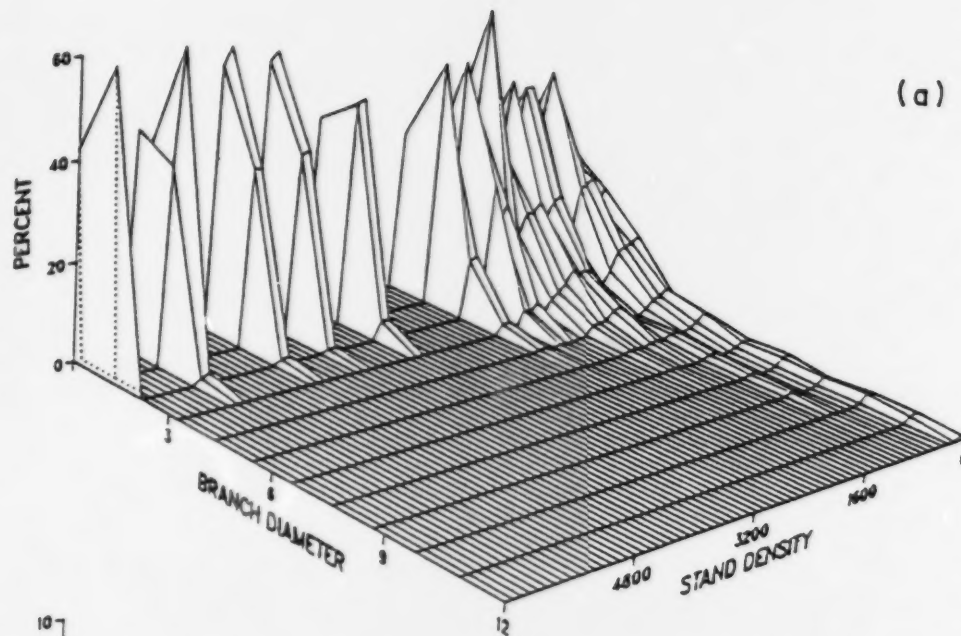


FIGURE C5. Relationship between branch number (as percentage of total numbers of branches on the first log of lodgepole pine), branch diameter (in centimetres) and stand density (trees per hectare). (a) All branches. (b) Living branches. (Ballard and Long 1988).

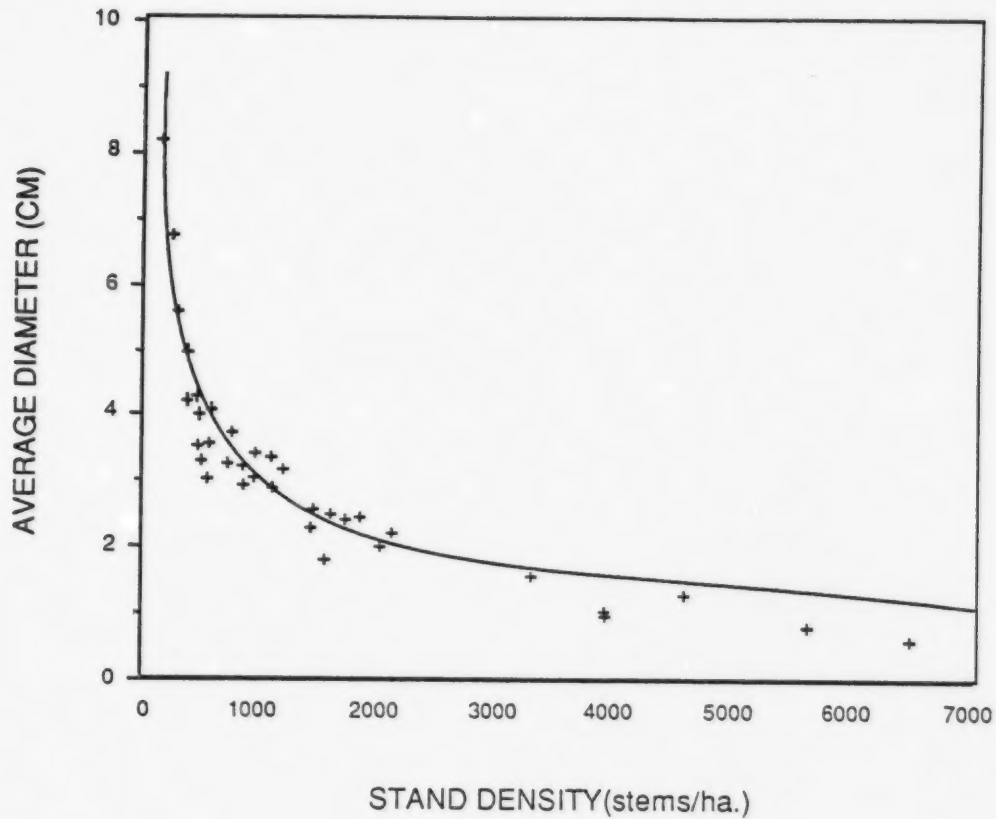


FIGURE C6. Average diameter of the five largest branches on the first log (4.7 m) of lodgepole pine as a function of stand density (Ballard and Long 1988).

Trees with significant taper have relatively low lumber yields and they are unacceptable for the manufacture of some specialty products such as poles. Tree taper is maximized when the crown is at its maximum size (before and just after crown closure). "As distance between the live crown and the base of the stem increases, proportionately more growth occurs at the top of the first log than at the base, thus reducing taper of the first log" (Ballard and Long 1988).

Barrett (1981) concluded that 77-year-old white spruce (site index 20 at 50 years) had insignificant difference in taper between 623 trees/ha and 894 trees/ha. Sjolte-Jorgensen (1967) reported that whole-stem log taper was 1.13 cm/meter at 3 m spacing and 1.04 cm/m at 2 m spacing.

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APPENDIX D

Economic Analysis Tools
for Crop Planning



ECONOMIC ANALYSIS TOOLS FOR CROP PLANNING

Overview

Economic or Benefit-Cost Analysis (BCA) refers to a set of procedures enabling analysts to evaluate the economic desirability of one or more projects. As long as a project has an economic dimension, as most do, it can be evaluated using BCA techniques.

The general purpose of BCA is to enable an agency to identify projects creating the largest monetary benefit (Anon. 1976; Mishan 1973). A government analyst may evaluate whether society is economically better off if one particular project is undertaken, or may recommend one (or more) most socially beneficial project(s) from a number of alternatives. A private analyst would answer such questions from the perspective of a firm. The economic attributes of a project can be evaluated using several, somewhat different rationales, and thus there have emerged several benefit-cost measures or tools. Furthermore, since these measures focus on different aspects of project costs and benefits, the ranking of a given set of projects may depend on which tool is used, especially when the project is complex.

The use of financial analysis in forest management has been criticised by various authors (Fearnside 1989). Specifically, Baskerville (1989) questioned the reality of determining economic indicators on a stand-level basis except for choosing among alternative site treatments to achieve a specific change in a year for one stand in one rotation.

Important to the application of this crop-planning process is the understanding that the main utility of using economic analysis tools at the forest-class is to rank alternative management options that have equivalent outcomes and not to determine actual profit or costs at the forest level. The

economic analyses in this paper are applied mostly in a relative rather than absolute sense.

The following notes explore how PNW and BCR could be used in crop-planning. For two reasons the conclusions reached below will not be in the form of a set of rules to delineate when BCA should be used in one way or another. First, it is not possible to encompass every possible situation in a simple set of rules; indeed, it may not be possible no matter how complex one is willing to make the set of rules. Second, since the different BCA tools evaluate different characteristics of a project, it follows that different information is provided by each measure (see also Anon. 1976). It is recommended that more than one economic tool be used in examining a project, even if the forester subsequently decides that the specific circumstances make one yardstick or tool more relevant than another.

Economic Indicators

The first goal of crop planning is to achieve the forest objectives by developing appropriate forest-level harvest and silvicultural strategies. A wide range of measurable forest and stand-level measures can be used for assessment of various options (Table D1). Wildlife and recreational indicators are also important, but are not included in this version of the crop-planning process.

Relative cost-efficiency can be measured at both the forest and forest class levels. At the forest level, various generic silvicultural or management strategies that can achieve the forest management objectives can be compared and the most cost-efficient selected (e.g., planting versus natural seeding plus pre-commercial thinning).

TABLE D1. Forest-level and forest-class indicators.

Forest	Forest Class
Level of Growing Stock (GS)	Volume per ha
Species Mix	Species Mix
Size and Quality of GS	Size and Quality of Wood
Forest Increment	Mean and Current Annual Growth
Harvest Level	Minimum Harvest Age
Age-Class Structure	Age-Class Structure
Level of Wildlife Habitat (WH)	Quality and Type of WH
Quantity of Recreation opportunity (RO)	Quality and Type of RO
Level of Silviculture	Type of Silviculture

In the initial forest analysis, required changes in stand yield performance are determined. At the forest-class level, the cheapest way to make the change is determined.

Economic values could be applied to each of the forest or forest class indicators listed in Table D1, but most important are values associated with forest growth and levels of silvicultural activity, since these (if economic values are added) represent the relative benefits and costs associated with the forest or forest class. Not included but also important in the present version of the crop-planning process are harvest costs relative to the various stand types created. The economic indicators providing benchmark assessment values include: silviculture cost/m³ of wood produced, net profit produced, and ratio of revenue over cost.

Types and Uses of Benefit-Cost Analysis Tools in Crop Planning

There are several BCA tools widely used in forestry. These include present net worth (PNW) (also called maximizing net revenue and by several other names), the benefit/cost ratio (BCR), and the internal rate of return (IRR). PNW is the sum of discounted benefits minus the sum of discounted costs and the BCR is the sum of discounted benefits divided by the sum of discounted costs (see Appendix A).

(1) $PNW = \text{total discounted benefits} - \text{total discounted costs}$

(2) $BCR = \text{total discounted benefits} / \text{total discounted costs}$

IRR is the discount rate which sets the value of the PNW in equation (1) equal to zero. It is difficult to see how this contributes insight that the BCR does not.

As the equations show, PNW expresses the size of the net benefit or profit obtained, whereas BCR expresses the effectiveness of a unit of cost at producing benefits. The IRR is the compound rate of value growth during a project (Mishan 1973; Nautiyal 1988). A discussion of the steps in conducting an analysis can be found in Anon. (1976) and Nautiyal (1988).

A PNW of zero means a project will just break even, and a project with the largest PNW would be the most favourable when PNW is the assessment tool. A BCR of one (1.0) is obtained if a project breaks even, and the largest BCR is most desirable. A project will be economically desirable if the IRR exceeds the rate of return earned on the most profitable alternative investment. The highest IRR is preferred.

For the forest manager, determining PNW answers the question: "What forest-level silvicultural strategy will give the greatest profit?" This

economic yardstick could be applied to forests consisting of prime sites, private land, or any forests in which the objective is to maximize revenue.

Alternatively, BCR could be used when the manager has to produce wood at the least cost. This measure is used as a gauge of economic efficiency, rather than for maximization of profit. Managers with limited budgets (not enough to do the job) would favour this technique.

The oft-cited advantage of the IRR is that the discount rate need not be selected. This would be an important advantage if it were completely true, but it is not, since a project is only worthwhile if the IRR exceeds the rate of return that could be earned in an alternative investment. Thus, judging the feasibility of a project usually involves selecting a discount rate.

When a BCR is calculated, care must be taken to ensure that negative side-effects are treated consistently (Anon. 1976). Some analysts treat all negative effects as costs while others view negative outputs as negative benefits. The choice made affects the value of the BCR. Inconsistent procedures can render the BCR values erroneous. Such problems arise most frequently when dissimilar types of projects are compared (e.g., wildlife vs. timber production).

PNW and BCR can both be used to evaluate a forest-wide program based on forest-class ground rules. However, use of the IRR is difficult to justify for most realistic forest-wide scenarios because it only identifies the best projects when the entire net proceeds from an investment can be re-invested to earn the same rate of return. This implies that projects can be repeated in a proportionally expanded form. Since the forest landbase is limited, this condition cannot hold indefinitely, so IRR is not appropriate. It is therefore not included in the crop-planning process.

The PNW and the BCR measure different economic aspects of a project and do not provide the same information. Therefore, the two criteria will not necessarily rank a given set of projects in the same order. The PNW value indicates nothing about the efficiency of the investment, whereas the BCR does not describe the size of the project's returns or profit. A frequently asked question is: "Which indicator is best?" Virtually unanimous support is found for the use of PNW as a ranking criterion when only one option may be selected and there are unlimited funds (Hirshleifer 1970; Mishan 1973; Anon. 1976; Clutter et al. 1983; Nautiyal 1988). However, the issue is more complicated in other cases. Suppose two projects are being compared. The associated discounted costs, benefits, and statistics are shown in Table D2. If the budget is unlimited, and if 10 ha are eligible for treatment, then it would be best to plant all 10 hectares since \$3,000 would be earned as compared to \$1,000 for seeding (for planting and seeding, Benefits-Costs $\times 10 = \$3,000$ and \$1,000 respectively). The selection of the option with the "best" PNW value would achieve the management objective which is to maximize profit.

TABLE D2. A hypothetical comparison of seeding and planting.

Project	Cost (\$/ha)	Benefit (\$/ha)	PNW (\$/ha)	BCR
Planting	400	700	300	1.75
Seeding	50	150	100	3.00

However, if there is a limited budget of \$500, the greatest net benefit is obtained by maximizing the average efficiency of the investment by selecting the option with the "best" BCR. The optimum action is to seed the entire area which produces \$1,000 of revenue versus planting 1.25 ha which provides only \$375 worth of net revenue. When comparing the two, it becomes evident that the old saying "it takes money to make money" applies.

If the budget were increased to \$2,000, then planting 4 ha and seeding 6 ha would be the best choice. This choice cannot be deduced by looking at just one indicator because the budget and available area both affect the decision. When applying the process to actual forests, what is determined to be the best economic choice for a particular stand is not necessarily the best for the whole forest because of age-class structure and budget. This shows that there is no single rule which can be applied to all situations, and the trial-and-error skills of the manager will always be tested.

Where Does Benefit-Cost Fit in Crop Planning?

Forest-Class Economic Analysis

The PNW and BCR tools outlined in the previous section can be applied directly to determine the most cost-efficient silvicultural ground rule that will result in stand growth following the desired yield curve. However, the economic results determined should not be taken in an absolute but rather a relative sense. In a forest consisting of many stands, the forest-level return on investment is not a sum of the individual stand economic analyses. Individual stand harvest occurs when the stand is operable and needed to contribute to forest level benefits as compared to when the stand harvest will maximize the return on investment for that individual stand.

Faustmann's (1849) economic process is the basis for most economic tools. He evaluated forest investment based on the funds invested (costs) and returned on the same piece of land or forest stand. Faustmann's "bare land" concept assumes a stand is mutually exclusive of its adjacent stands. In a real forest, the timing of stand harvest is driven by the unique dynamics of the forest and the silvicultural and harvest strategies that provide desired benefits. An evaluation may conclude that the best economic value of a stand is to harvest it at age 50. However, when such a stand is part of a forest dominated by overmature age classes, application of an oldest-first harvest rule may lead to the stand in question being harvested at age 80 years. The stand-level economic parameters are irrelevant for the stand in the context of the dynamics and structure of the entire forest.

Forest-class or stand economic analysis does provide relative cost-efficiency values when comparing silvicultural options that have similar growth functions. In the three example forests studied, generic growth functions for various forest classes were developed in the initial forest analysis, while the forest-class analysis provided the option with the lowest costs and most benefits.

Forest-Level Economic Analysis

The economic analysis tools of PNW and BCR can also be applied in analysis of the allowable cut effect (ACE). The major difference with other uses is that the values are not discounted when annual costs and revenue are at constant levels.

1. $PNW = \text{total benefits (annual harvest} \times \text{value per m}^3) - \text{annual costs (area treated} \times \text{cost/ha)}.$
2. $BCR = \text{total benefits/total costs}.$

In our examples, both the PNW and BCR values are abnormally high because the value per m^3 is based on provincial value added. In an industrial setting for private land, the benefit measured would be profit per m^3 . Profit per m^3 would be based on the expected end product (e.g. pulp, paper, stands).

Another approach for measuring PNW and BCR is to use a marginal value rather than total. In Example One in the text, the forest is producing 97,000 m^3 /yr without silviculture and with silvicultural expenditure can produce up to 125,000 m^3 /yr. Instead of using total benefits, substitute marginal benefits (net revenue increase; revenue for 125,000 m^3 /yr - revenue for 97,000 m^3 /yr) and that will determine a BCA for the actual benefits created by silvicultural investment. This type of calculation was used exclusively in this report.

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